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Sustainable Industrial Engineering along Product-Service Life Cycle/Supply Chain

Edited by
João Carlos de Oliveira Matias, Susana Garrido Azevedo and Carina Pimentel

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Preface to ”Sustainable Industrial Engineering along Product-Service Life Cycle/Supply Chain”

To try to answer the challenge of developing sustainable societies, supply chains are compelled to reinvent their processes and practices by continuously incorporating sustainability guidelines into their decisions. The International Institute for Sustainable Development defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. To tackle this challenge, supply chains and society in general must respond effectively to today’s environmental, economic and social challenges.

Industrial engineering is concerned with value creation, building a bridge between technology and management. Development of new technologies can only take place if technologists and engineers have a good understanding of the needs of those who will be affected by new technologies. Engineering innovations need to respond to social demand while taking ecological and economic principles into account. The design, operation, and assessment of such sustainable manufacturing systems within the limitations of renewable resource generation and social compatibility are major challenges in the 21st century. This concern contributes to enhancing the importance of controlling the product service along its lifecycle using the methodology of sustainability life cycle assessment for assessing the economic, environmental, and social performance of a product service, from cradle to cradle. Cleaner production is also a concern for sustainable industrial engineering systems aimed at making a more efficient use of natural resources and reducing the generation of wastes and emissions at the source, through the implementation of some practices, such as technology modification, sustainable operations, reduce, recycling and reuse, and product modification. Cleaner production strategies, industrial symbiosis, and eco-efficiency strategies are amongst some tools of sustainable industrial engineering which can help in the achievement of sustainable engineering solutions. These sustainable industrial engineering practices along the supply chain help to reverse the adverse effects of the industry, and the use of environmentally friendly and socially beneficial practices may help to improve business profitability.

Sustainable industrial engineering addresses the issue of the sustainability of industry from an economic, an environmental and a social and societal point of view. Its application fields are the whole value chain and lifecycle of products/services, from the development to the end-of-life stages. This book focuses on how sustainable industrial engineering can contribute to supply chains becoming more sustainable.

João Carlos de Oliveira Matias, Susana Garrido Azevedo, Carina Pimentel
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Article

The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation

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Abstract: Industrial symbiosis, which is characterised mainly by the reuse of waste from one company as raw material by another, has been applied worldwide with recognised environmental, economic, and social benefits. However, the potential for industrial symbiosis is not exhausted in existing cases, and there is still a wide range of opportunities for its application. Through a comprehensive literature review, this article aims to compile and analyse studies that focus on potential industrial symbiosis in real contexts, to highlight the margin of optimisation that is not being used. The cases reported in the publications identified here were characterised and analysed according to geographic location, type of economic activity, waste/by-products, main benefits, and the methods employed in the studies. From this analysis, we conclude that there is great potential for applications involving industrial symbiosis throughout the world, and especially in Europe, corresponding to 53% of the total cases analysed. Manufacturing stood out as the sector with the highest potential for establishing symbiosis relationships, and the most common types of waste streams in potential networks were organic, plastic and rubber, wood, and metallic materials. This article also discusses the main drivers and barriers to realising the potential of industrial symbiosis. The diversity of industries, geographical proximity, facilitating entities and legislation, plans, and policies are shown to be the main drivers.

Keywords: industrial symbiosis; potential industrial symbiosis; sustainability; eco-industrial parks; circular economy

1. Introduction

In recent years, resource-intensive use, rising industrialisation and urbanisation, modern lifestyles, energy-intensive use, and land use patterns have led to increased greenhouse gas emissions, with negative consequences for the environment and the population [1–3]. It is therefore urgent to find solutions that do not hinder economic development but can provide ways to reduce carbon dioxide emissions, which are largely responsible for greenhouse gases, and to use resources more efficiently. As a subfield of industrial ecology, industrial symbiosis, which is often defined as a collective approach in which one company's waste is used as raw material by another company [4], can help to address these problems without compromising economic development. This practice is similar to biological processes, in which different organisms associate in a "mutually beneficial relationship" [5], as it allows entities and companies that operate separately to come together in the physical exchange of materials, by-products, energy, and water, with competitive advantages for all participants [6]. In addition to waste/by-product exchanges, this sharing of resources also encompasses infrastructure sharing and the joint provision of services [7,8].

Some of the problems faced by industries, such as increases in waste, waste treatment costs and high resource consumption, are common in urban areas [9–11]. Thus, if cooperation between companies is extended to urban regions, there is potential for both parties to achieve environmental and economic benefits and to mitigate certain common problems. This cooperation has been referred to in several publications as Industrial and Urban Symbiosis (also called Urban and Industrial Symbiosis) and takes place when waste generated in an urban area is used as a raw material or energy source in industry or when industries provide urban areas with waste heat resulting from their operation [12,13]. However, some authors have also used the term Urban Symbiosis to refer to the use of waste from urban areas as a raw material or source of energy [14–16].

The most well-known case of industrial symbiosis, and the one most often cited in the literature, is in Kalundborg, Denmark. This network arose spontaneously from a self-organising initiative between companies to address water scarcity [4,5,17] and over the years has increased not only in terms of the number of symbioses but also the number of participants and remains a successful case to this day.

However, industrial symbiosis is not confined to the Kalundborg case, and numerous examples of synergistic networks around the world have been reported in the literature, with a wide variety in terms of the numbers of participants, types of economic activities, and how they are organised. In Europe, numerous foci of industrial symbiosis [18] are spread across different countries, and most of the cases reported in the literature are in northern and north-western Europe, with the United Kingdom reporting the highest number of cases [19]. This is due to the voluntary programme that the government has launched to help companies find partners to use their waste as raw material, called the National Industrial Symbiosis Programme [20]. Finland also has several cases of industrial symbiosis, largely arising from the strong presence of the pulp and paper industry, which has driven the creation of synergy relations [21,22]. In Asia, a number of industrial symbiosis initiatives have also been reported, with the highest number of cases in China, largely due to constraints on carbon dioxide emissions and the numerous plans and policies that have been implemented to foster circular economy practices [23–25]. In Japan, there have been cases of industrial symbiosis and industrial and urban symbiosis across several cities, driven by the Japanese Eco-Town Programme that encourages the use of industrial, municipal, and commercial waste in industrial applications, with the aim of boosting the economy and reducing waste disposal [14,15]. In North America, and particularly in the US, there have been cases of industrial symbiosis that date back to the late 1970s. The case most frequently mentioned in publications is located in Barceloneta, Puerto Rico, where the strong presence of pharmaceutical companies has spurred the creation and development of industrial symbiosis between various companies [26,27]. Several cases of industrial symbiosis have also been reported in Australia [28,29], Brazil [30], Morocco [31], and Algeria [31].

Despite the recognised benefits that these synergy cases have provided to the environment, the companies involved and the local population, the potential for industrial symbiosis is not exhausted in these existing cases, and there is still great potential for application not only in developed countries but also in countries with developing economies. Of the various articles published on industrial symbiosis, a significant proportion have focused on the best ways to foster industrial symbiosis and the most effective ways of overcoming the various obstacles, including economic, technological, legal, and social obstacles, that are faced in the creation and development of industrial symbiosis. Although some of these publications have a predominantly theoretical content e.g., [23,32,33], most present in-depth studies conducted in real contexts, that is, in a given region, with a holistic analysis of those industries, wastes and products with potential for developing industrial symbiosis e.g., [34–37]. In some of these studies, the implications of these new synergies for the environment, the economic development of companies, and the surrounding population have also been studied e.g., [36,38,39]. This article focuses on the latter type of publication, and identifies these as cases of potential industrial symbiosis. All articles that study the possibility of implementing new industrial symbiosis relationships in a given location and that indicate the types of economic activities and industrial symbiosis are included in this designation.

The various studies that have been carried out on potential cases of industrial symbiosis have a wide scope, not only in terms of the characteristics of the synergy network but also in terms of the existence or otherwise of industrial symbioses in the location under study. In places where symbiosis networks already exist, relationships of trust are already established, and there is a knowledge of the benefits of this practice that can help to facilitate the process of mobilising other companies. Studies carried out of the industrial symbiosis networks in Weifang Binhai Economic-Technological Development Area, China [40], in the Västra Götaland region of Sweden [41], and in the Taranto provincial industrial district in Italy [42] represent some of these examples. In these cases, proposals have been put forward to extend the industrial symbiosis network to other companies, with the aim of repurposing some of the waste that was not yet being shared. However, several studies have been published that have proposed the creation of industrial symbiosis relationships in areas where this practice is not yet implemented but bring together a set of characteristics that reveal the potential for establishing synergy networks. Examples include studies of the development of industrial symbiosis carried out in Perth and Kinross, Scotland [43], Botoșani and Piatra Neamţ in Romania [44], and Konia, Liberia [45].

Although the potential for the application of industrial symbiosis is high, there are a number of constraints on its implementation. A lack of trust, uncertainty about the benefits, a lack of knowledge of the concept of industrial symbiosis, and a lack of information sharing [20,33,34,46–48] are the main factors that have been identified as restraining this process. However, there are also factors that are often referred to as drivers for the creation and development of industrial symbiosis networks, such as the need to reduce raw material and waste disposal costs and the potential generation of revenue [18,34,49–51]. In addition to these aspects, existing policies and legislation have also been identified as influencing industrial symbiosis practices. Regulatory pressure and landfill tax, which drive companies to find solutions for using resources more efficiently and reducing waste disposal [50,52], are examples of these. Policies and plans that aim to foster synergy networks, such as those in China [23,25] and the United Kingdom [20], have greatly contributed to the spread of these practices. However, existing legislation can also restrict these practices, for example if it is unclear or very restrictive on the use of waste, and can thus create difficulties for companies with regard to the application of industrial symbiosis [53].

A literature review reveals that although there are many studies of the compilation and analysis of case studies relating to industrial symbiosis [18,19,23,54–58], these focus on synergies that have already been implemented. Furthermore, although a study of the evolution of industrial symbiosis was carried out by Chertow and Park [59], with an analysis of the number of articles published and the countries that were the subject of the various publications, this work only included articles published until 2014. A comprehensive analysis of the cases of potential industrial symbiosis is still absent.

This article therefore aims to compile and analyse the various cases of potential industrial symbiosis in real contexts reported in the literature, and to highlight the margin of optimisation that is not being used. It also aims to identify and discuss the main drivers and barriers to the implementation of industrial symbiosis, as well as the various strategies for overcoming these barriers. To this end, the various cases are characterised and analysed by geographical location, type of economic activity, type of waste/by-product exchange, infrastructure sharing, and joint provision of services. Moreover, the methods employed in the different cases are analysed, as are the main environmental, economic, and social benefits that would be achieved if industrial symbiosis were to be realised. The cases of potential industrial symbiosis have been separated into those concerning the symbiosis between industries and those concerning the manufacture of new products and new uses for the different wastes enhanced by industrial symbiosis.

The rest of the article is organised as follows. Section 2 describes the methodology adopted for the research, selection, and analysis of publications, as well as the inclusion and exclusion criteria.

Sections 3 and 4 contain the results and a discussion. Section 3 presents the results and an analysis of the cases of potential industrial symbiosis, in terms of the companies involved, the production of new products and new uses of waste. Section 4 discusses the main drivers, barriers, and strategies for overcoming these barriers to the creation of industrial symbiosis networks. Finally, Section 5 presents the main conclusions and discusses the limitations of this study and the scope for future research.

2. Materials and Methods

In order to fulfil the proposed objectives, a methodology was developed consisting of several stages, as illustrated in Figure 1. This methodology can be grouped into three main steps: a deep and systematic collection of the existing literature, the selection of publications and a content analysis.

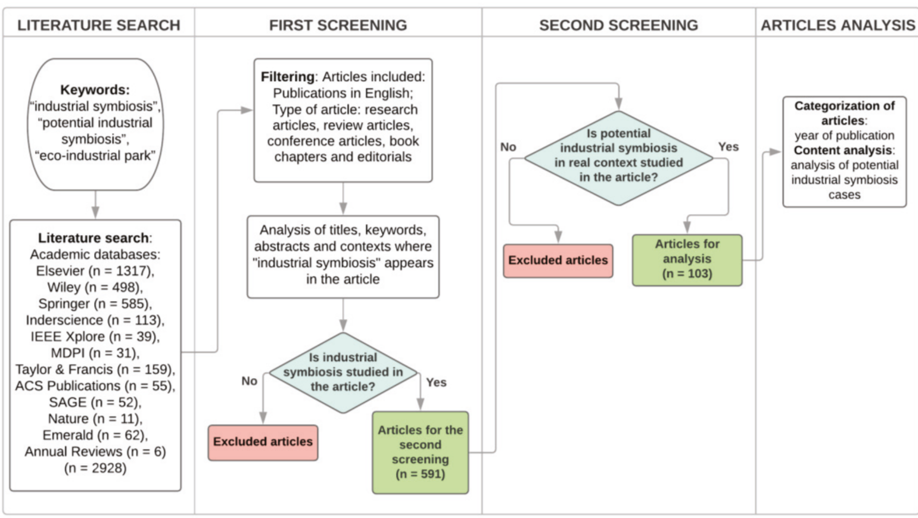

Figure 1. Flow diagram of literature search and screening.

To enable a systematic and thorough review of the existing literature, several steps were followed. The first was the choice of keywords. To avoid limiting the search and thus obtain a more comprehensive set of publications, the terms "industrial symbiosis", "potential industrial symbiosis", and "eco-industrial park" were combined. These were used to search for articles in databases with more publications in this area, such as, Elsevier, Wiley Online Library, Springer, MDPI, Inderscience Online, IEEE Xplore, Taylor & Francis Online, ACS Publications, SAGE Journals, Nature Research, Emerald Insight, and Annual Reviews. In this research, no time interval was imposed, and the only exclusions were articles that were not written in English. The publications that resulted from this initial collection were submitted to a screening process in order to select the most relevant ones for the study. Titles, keywords, and abstracts were read, with the aim of selecting articles that focused mainly or significantly on industrial symbiosis. If there were any doubts about the inclusion of the articles, we analysed the frequency with which the keywords appeared throughout the publication and the context in which they were inserted in order to verify whether industrial symbiosis was the focus of the study or whether it only appeared as an example or to contextualise other concepts. This selection resulted in 591 publications, including research articles, review articles, conference articles, book chapters, and editorials. In our analysis, the references cited in these publications were used as secondary sources; however, this resulted in only a few articles, which may indicate the wide-ranging of the initial research.

In the next step, the 591 articles on industrial symbiosis were screened with the aim of finding only the publications whose object was the study of potential industrial symbiosis in a real context. This resulted in 103 articles, and these made up the final body of articles for which a more detailed content analysis of potential industrial symbiosis was carried out. Of these 103 articles, 89 concerned industries and 14 concerned potential uses of industrial symbiosis to manufacture new products or use different wastes. A content analysis of all these articles was then conducted to gather and analyse information on potential industrial symbiosis, such as location, types of economic activities involved in potential synergies, types of waste/by-products, and the existence or otherwise of infrastructure sharing. We also analysed the methods employed in the different analyses, the main environmental, economic and social benefits, and the factors underlying the potential for creating industrial symbiosis, which may condition or favour it.

3. Potential Industrial Symbiosis

The results of the study are presented below and are structured according to the main themes that emerged from the research and analysis of publications on potential industrial symbiosis, namely its scope, evolution over time, geographical distribution, and cases of potential industrial symbiosis relating either to companies or to the production of new products or new uses of waste.

3.1. Evolution of the Number of Published Articles

Of the 591 articles on industrial symbiosis selected and analysed according to the selection criteria defined in Section 2, 103 related to potential industrial symbiosis, accounting for approximately 17% of the total. Although these articles on industrial symbiosis were published from 1995 onward, it was only around 2001 that articles on potential industrial symbiosis began to appear, as illustrated in Figure 2.

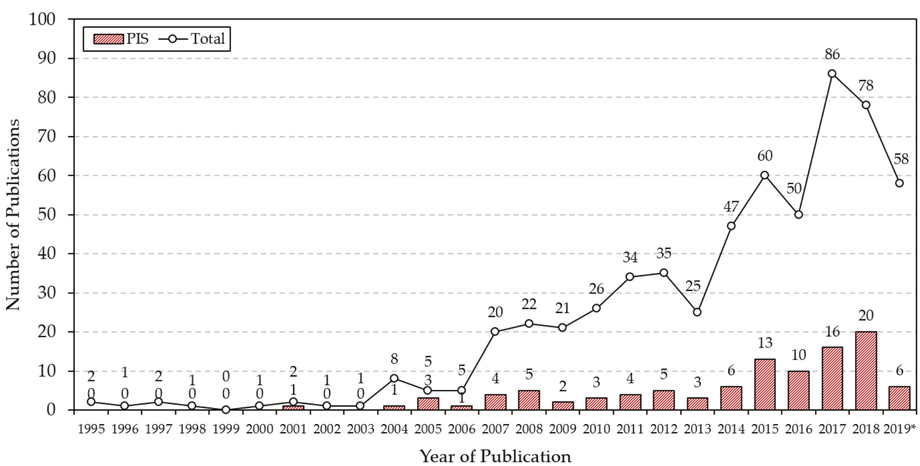

Figure 2. Number of publications on industrial symbiosis and potential industrial symbiosis (PIS) per year.

Figure 2 shows the growing evolution of the number of publications on industrial symbiosis. Although low numbers of studies were published during the early years, from 2007 onward, there was a growth in the number of publications, which continued over the following years. Despite these small numbers, publications on potential industrial symbiosis have also shown growth. The evolution of these publications essentially comprises two distinct periods. In the first, between 2001 and 2014, there was a greater oscillation between the number of publications and in which the growth of articles was not very significant. In the second, between 2015 and the current year, more pronounced growth could be seen, and whilst there was a drop in 2016, this was insignificant in light of the increase over the following years. Although this second period was shorter in terms of years, the proportion of publications was clearly higher than those in the first and accounted for 63% of the total number of publications. This increase coincided with the increase in publications on industrial symbiosis, and although it began to grow more significantly from 2007 onward, it was from 2014 onward that it began to obtain greater expression, revealing the growing scientific interest in this issue and the recognition of its potential to achieve sustainability in terms of its environmental, economic, and social aspects.

The proportion of the articles on potential industrial symbiosis in relation to the total number of publications on industrial symbiosis did not show significant variation over the years, except for 2001 and 2005, in which these articles made up 50% and 60% of the total number of publications, respectively. Three periods are of note, due to the fact that the values were very close in consecutive years—the period between 2006 and 2008, with an average of 20% of the total number of publications on potential industrial symbiosis; the period between 2009 and 2014, with an average of 12%; and the period between 2015 and 2018, with an average of 21%. Most of these 103 publications (about 84%) relate to research articles, while 12% are conference papers, and the remaining 4% are book chapters.

3.2. Geographic Distribution

The study of potential industrial symbiosis has shown great diversity with regard to geographical location; it has been studied in 31 different countries, revealing the great potential of this practice both in developed countries and in countries with emergent economies, as illustrated in Figure 3. Europe leads in terms of the number of publications on potential industrial symbiosis, with 48 articles, corresponding to approximately 53% of the total published. It is followed by Asia, with 26 publications, corresponding to 29% of the total, and North America, South America, and Oceania, with six, four, and four publications, respectively, corresponding to 7%, 4%, and 4% of the total. With three publications, equivalent to 3% of the total, Africa has the fewest studies of potential industrial symbiosis. This distribution is very different from that presented for industrial symbiosis publications [59]; here, China very significantly predominates in terms of publications, followed by the US and Australia.

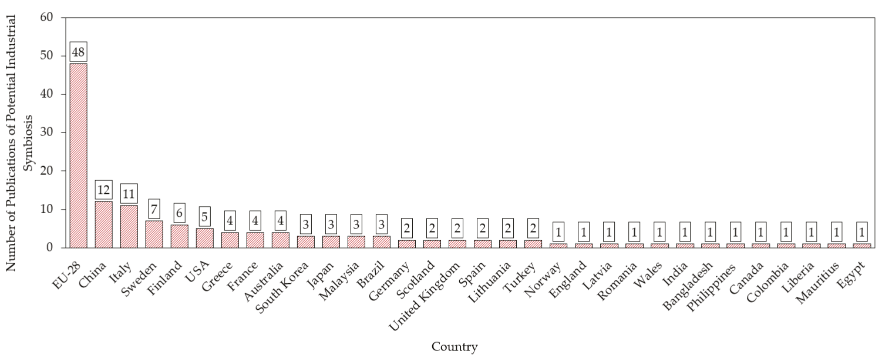

Figure 3. Distribution of the number of published studies on potential industrial symbiosis by country.

The European countries in which most case studies of potential industrial symbiosis were carried out were Italy, Sweden, and Finland, with 11, seven, and six articles, respectively. All cases in Sweden were related to the study of potential industrial symbiosis between industries, while those in Italy and Finland focused both on synergies between industries and on the investigation of waste and new products fostered by industrial symbiosis.

Of the eight countries in Asia with studies of potential industrial symbiosis, most related to China, with approximately 46% of the total for Asia.

The US occupies the fifth place on the list of countries with articles published on potential industrial symbiosis, with three articles focusing on the synergy between industries and two more on the study of new uses for waste produced by the automobile industry. This figure is still low compared to the countries with the most publications, which is also true for case studies of industrial symbiosis—although the USA occupies second place on this list, the difference between the number of articles published compared to China, which ranks first, is very significant [19]. While some incentive measures have been applied to create synergies, such as an Environmental Protection Agency–funded project to identify possible synergies in six counties in North Carolina [60], they have not had a major impact on the increase in cases of symbiosis, and even existing studies of potential industrial symbiosis between industries date back many years.

In recent years, studies have been carried out to analyse the implementation of industrial symbiosis practices in developing countries such as the Philippines, Liberia, India, Bangladesh, Colombia, Mauritius, and Egypt. While these countries have little in the way of a tradition of synergy practices between companies and the number of published case studies is still small [19], the important role of industrial symbiosis is recognised as a means to enhance the development of these regions [34,45,61].

3.3. Cases of Potential Industrial Symbiosis

Although industrial symbiosis is well established in many countries, there are still many possibilities for creating and developing new industrial symbioses. The numerous studies that have proposed and evaluated new synergy networks are examples of this. In places where there is already industrial symbiosis, the process of creating new relationships is facilitated, since there are already relationships of trust between the actors and the benefits offered by this practice are well known; however, this is not an essential factor. In places where there is no synergy, factors such as the location, the waste generated, or the nature of the industries can drive the creation of symbiosis relationships. Moreover, this potential is not bound to a particular region, country, type of activity, or number of entities (NE) involved, as proven in the many studies that have been performed to evaluate the creation of new industrial symbioses (shown in Table 1). This table summarises the main characteristics of the various cases of potential industrial symbiosis that have been published (Table A1 in Appendix A provides more details of these cases). By analysing Table A1, it is possible to verify the huge untapped potential and the huge diversity of opportunities for the development of industrial symbiosis. These cases are characterised by the location, number of entities involved (NE), type of economic activity, waste/by-product exchange, sharing of infrastructure, joint provision of services, methods used in the study, and assessment of the potential of industrial symbiosis. The various economic activities are grouped into sections, which are defined according to the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Of the 21 sections defined in the ISIC, 16 are relevant to the various cases of potential industrial symbiosis. In Table 1, the section designations are more concisely defined. The different streams of waste exchanged in these cases are grouped into types, such as organic (e.g. food and food processing wastes, biomass, livestock and fisheries wastes); plastics and rubber; wood; metallic; non-metallic (e.g. glass, waste from construction and demolition, lime-based waste), paper, waste heat and steam; ash, water, and wastewater; chemicals; sludge; waste oil; and others (e.g. textile waste).

Table 1. Potential industrial symbiosis applications and analysis studies.

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Europe				
Italy	Murano		Manufacturing	Chemicals	Water treatment	BATTER tool, direct measurements	2007	[62]
	Brancaccio, Carini, and Termini Imerese		Manufacturing	Plastics and rubber		Questionnaire and interviews, life cycle assessment	2010	[63]
	Val di Sangro Industrial Area	19	Manufacturing		Collective management of scraps	Questionnaires, interviews, site visits, and focus groups	2014	[64]
	Fucino upland		Agriculture and manufacturing	Paper, plastics and rubber, and wood	Common local recycling platform	On-site survey and interviews.	2015	[65]
	Emilia-Romagna		Agriculture and manufacturing	Organic, sludge, paper, non-metallic, wood, and others		Interviews, guided collective discussion, visits to laboratories, and conferences	2015	[53]
	Catania and Siracusa districts		Agriculture, manufacturing, energy, water and waste, construction, sale and repair, transportation and storage, information and communication, professional and scientific activities, administrative and support service, education, human health and social work, and other service activities	Water and wastewater, organic, sludge, wood, metallic, waste oil, plastics and rubber, chemicals, non-metallic, and paper	Energy, equipment, expertise, and services	Invitation emails and phone calls, meeting tables	2016	[66]
	Brescia	12	Manufacturing, energy, and public administration	Metallic, wood, sludge, and waste heat and steam		SWOT analysis	2017	[67]
	Brescia	2	Agriculture and manufacturing	Chemicals		Economic model	2018	[35]
	Province of Pescara		Agriculture, manufacturing, water and waste, and construction	Organic, metallic, non-metallic, paper, plastics and rubber, waste heat and steam, and water and wastewater		Qualitative analysis and critical analysis	2017	[11]
	Marche Region	3	Manufacturing and water and waste	Plastics and rubber		Web platform, economic assessments, life cycle assessment	2018	[38]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden	Small town in southern Sweden		Manufacturing, energy, water and waste, and the municipality	Waste heat and steam, wood, organic, ash, sludge, and paper		Interviews and group discussion, direct observation and participation at the sites, mass and heat balances over the system	2005	[68]
		4	Manufacturing and energy			MIND method	2008	[69]
		4	Manufacturing and energy	Organic, waste heat and steam, and wood		MIND method. Commercial optimization solver, assessment of CO_2 emissions	2008	[70]
	Luleå, Borlänge, Finspång, Sandviken		Manufacturing and energy	Waste heat and steam and Chemicals		System perspective evaluation	2011	[71]
	All 290 municipalities		Agriculture, mining, manufacturing, energy, water and waste, and construction			Looplocal method, life cycle inventory	2015	[72]
	Västra Götaland		Agriculture, manufacturing, energy and water, and waste	Chemicals, ash, metallic, and water and wastewater		Top-down approach with three consecutive steps	2017	[73]
France	Territoire de la Côte Ouest		Agriculture and manufacturing	Organic		'Follow the Technology' method and Companion Modelling or Commod	2017	[74]
		7		Waste heat and steam		Mixed integer linear programming, direct method, key process indicators, sensitivity analysis, multi-objective model and Pareto front analysis, weighted sum method	2018	[75]
	16 regions		Manufacturing and energy	Waste heat and steam		Average energy intensity, production value, and heat consumption; spatial mapping methods and geographical information system; techno-economic model; linear programming problem	2018	[36]
	Salaise-sur-Sanne and Sablons		Manufacturing, water and waste, and urban areas	Industrial waste	Shared infrastructures	SWOT analysis	2018	[76]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Finland	Oulu		Manufacturing	Metallic, ash, and others		Literature review	2010	[77]
			Agriculture, manufacturing, water and waste, and municipality	Sludge and organic		Interviews, collaborative research approach, replication approach	2015	[78]
			Agriculture and manufacturing	Organic		Survey	2018	[79]
Greece	Viotia		Manufacturing	Metallic		Ontology engineering approach—eSymbiosis; metrics for industrial symbiosis benefits	2015	[80]
	Pili		Manufacturing, energy, and water and waste	Wood, ash, and organic	Utility sharing	Methodology to determine the most appropriate location and bioclimatic criteria	2017	[81]
	Achaia		Manufacturing	Water and wastewater and others		Interviews and visits	2017	[82]
Germany	Rhine–Neckar				Network structure, waste software, and intranet platform	On-site surveys	2004	[83]
	Central Germany		(i) Manufacturing; (ii) manufacturing and energy; (iii) manufacturing and energy	(i) Wood; (ii) wood and organic; (iii) wood		Communications and site visits; life cycle assessment and CML 2013 method	2018	[84]
Scotland	Perth and Kinross		Manufacturing and energy	Wood		Questionnaires and focus groups	2007	[85]
	Perth and Kinross		Agriculture, manufacturing, and energy	Wood		Questionnaire survey and an attitude survey	2007	[43]
Spain	Besaya	80	Manufacturing, construction, sale and repair, and transportation and storage	Waste oil, metallic, non-metallic, plastics and rubber, wood, waste oil, paper, organic, and others	Joint waste management	Questionnaires and visits	2015	[86]
	Cartes, Cantabria autonomous community	25	Manufacturing and construction	Organic, paper, etc.	Service or infrastructure	Georeferencing, geographic information systems, and application programming interface; SymbioSyS tool	2017	[87]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Lithuania	Jonava		Agriculture, manufacturing, water and waste, and administrative and support service	Waste heat and steam, organic, and sludge		Material flow analysis; material, energy and fuel balances; evaluation of environmental indicators and comparative analysis. Feasibility analysis	2016	[88]
			Agriculture and manufacturing	Organic		Indicators	2018	[89]
United Kingdom			Agriculture and manufacturing	Organic and others			2008	[90]
Norway	Mongstad	6	Agriculture, manufacturing, and energy	Chemicals and waste heat and steam		Mass and energy balance assessment, material and energy flow analysis, carbon and hydrogen flow analysis, CO_2 emission evaluation, and sensitivity analysis; hierarchy analysis method	2008	[91]
England	Five areas				Utilities-sharing	Habitat suitability mapping, and multi-criteria-evaluation mapping; sensitivity analysis	2012	[92]
Finland and Sweden	Gulf of Bothnia	7	Manufacturing	Metallic		Strengths and weaknesses assessment and common pool resource management analysis	2012	[93]
Latvia		2	Manufacturing and energy	Organic		Site visits, cumulative intensity indicator of a considered factor	2015	[94]
European country			Agriculture and Manufacturing	Chemicals and Water and wastewater		Concept analysis	2015	[95]
Romania	Botosani and Neamt		Agriculture, manufacturing, energy, water and waste, construction, sale and repair, accommodation and food, and administrative and support service	Chemicals	Infrastructure for utilities and supply process optimization	Interviews	2017	[44]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Asia				
China	Handan		Agriculture, manufacturing, and energy	Ash, water and wastewater, plastics and rubber, waste heat and steam, metallic, and others			2009	[96]
	Shanghai City and Jiangsu Province		Manufacturing and urban areas	Plastics and rubber, organic, and others		Divisia analysis, energy demand analysis, and regression analysis	2011	[97]
	Jinqiao		Manufacturing, energy, and water and waste	Sludge and waste oil		Experiments in a laboratory, life cycle assessment, total environmental impact	2011	[98]
	Yunfu	3	Manufacturing and energy	Chemicals and waste heat and steam		Production cost and sale revenue analysis	2011	[99]
	Shenyang		Manufacturing and transportation and storage			Coefficient of industrial agglomeration degree, Space Gini coefficient and Hector Fanta coefficient, logistic model, index of competitive analysis, expert evaluation method relational degree taxis	2012	[100]
	Guiyang		Manufacturing, energy, and commercial and residential area	Metallic, plastics and rubber, ash, waste heat and steam, and others		Questionnaires, material flow analysis, environmental benefit evaluation and CO_2 emission reduction, cost reduction	2015	[39]
	Guiyang		Manufacturing, energy, and commercial and residential area	Metallic, plastics and rubber, ash, waste heat and steam, and others		Questionnaires, material/energy flow analysis, process life cycle assessment, avoided consumptions and emissions, CO_2 emission reduction, hybrid physical input and monetary output model, hybrid life cycle assessment model integrating both process life cycle assessment and input–output model, life cycle emissions change, scenario analysis	2016	[9]
	Hangu, Tanggu, and Dagang Districts		Agriculture, manufacturing, and energy	Water and wastewater and others		Satellite images analysis, geospatial data processing and analysis software, manual visual interpretation and landscape type classification system	2015	[101]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
	Liuzhou	5	Manufacturing, energy, and communities	Plastics and rubber, ash, and others		Questionnaires, onsite survey, urban level hybrid physical input and monetary output model, hybrid evaluation model integrating process-based life cycle assessment and input-output analysis, calculation of increased or avoided consumption, trade-off emission, scenarios design	2017	[37]
	Liuzhou		Manufacturing, energy, and communities	Chemicals, waste heat and steam, plastics and rubber, and ash		Onsite survey, analytical approach integrating material flows analysis, and emergy evaluation model, avoided consumption and emissions and CO_2 emission reduction, emergy evaluation index and dilution emergy	2017	[10]
	280 proper cities and 357 county-level cities		Manufacturing, energy, and residential and commercial buildings	Waste heat and steam, ash, and metallic		Cross-sectoral symbiosis modelling; energy cascade algorithms; material-exchange algorithms; estimating reductions in fuel use, CO_2 and PM2.5 emissions, life-cycle analysis, and national-economy-wide economic input output-based life-cycle analysis; PM2.5 pollution and health benefit calculations and AERMOD atmospheric dispersion modelling system	2017	[102]
	Wuhan		Agriculture, manufacturing, and water and waste	Water and wastewater, sludge, and paper		Integrated life cycle management assessment method on the resource flows of industrial ecosystem	2019	[103]
South Korea			Manufacturing	Water and wastewater		Mathematical optimization model, general algebraic modelling system software, life cycle assessment and life cycle costing	2010	[104]
			(i) Manufacturing; (ii) manufacturing and urban area	(i) Others; (ii) wood and plastics and rubber		Interview, quantitative estimation of CO_2 emissions, uncertainty analysis	2015	[105]
	Ulsan		Manufacturing and/or urban area	Waste heat and steam		Interviews, scenarios analysis, heat load analysis procedure, CO_2 emission reductions, fuel cost reduction	2018	[106]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Shinchi Town		Manufacturing and energy	Waste heat and steam		Technical and economic feasibility assessment, sensitivity analysis, cost-benefit assessment and spatial analysis; energy generation model; energy distribution model; energy consumption model	2014	[107]
	Shinchi Town		Manufacturing, energy, and urban area	Waste heat and steam		Model framework including energy system design, land use scenario, inventory survey and geographic analysis; district heating network design and simulation; cost-benefit assessment; sensitivity analysis;	2018	[13]
	Tanegashima		Agriculture, manufacturing, and energy	Waste heat and steam, organic, and wood		interviews; scenario analysis, energy flow analysis; greenhouse gas emissions based on life cycle analysis	2016	[108]
Malaysia		4	Manufacturing and energy	Organic		Disjunctive fuzzy optimization approach; overall degree of satisfaction, annual gross profit, net present value, and payback period of a processing plant	2014	[109]
			Manufacturing		Cooperative safety management	Interview	2014	[110]
	Kedah		Manufacturing, energy, and water and waste	Chemicals, Plastics and rubber, Water and wastewater, and Sludge	Infrastructure sharing	Questionnaires. SWOT analysis. Materials Flow Analysis and the Input-Output data based on previous Life Cycle Analysis data	2017	[111]
Turkey	Gaziantep		Manufacturing, Energy and Water and waste	Organic, Plastics and rubber, Sludge, Chemicals, Non-metallic, Waste heat and steam, and Others		Industrial symbiosis match-making platform (ESOTA®, Industrial Symbiosis Opportunity Screening Tool). Visits and workshops	2017	[112]
	Ankara	10	Manufacturing	Waste heat and steam		Tool for defining data about companies and process, cleaner production potential and costs and environmental impact graph of processes. Analysis of mass balance and all materials	2018	[113]
India	Puducherry		Manufacturing			Survey method; trend analysis, causal chain analysis, policy analysis, training needs assessment, technology needs assessment, and barrier analysis; content analysis; SWOT analysis	2015	[114]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Bangladesh	Chittagong Export Processing Zone		Manufacturing, energy, and water and waste	Waste heat and steam, water and wastewater, and others		On-site energy audit and equipment/waste emission survey, visits, input and output analysis, feasibility analysis, business model development	2015	[115]
Philippines	Laguna					questionnaires and survey, decision making trial and evaluation laboratory	2016	[116]
North America								
USA	Six counties, North Carolina	87	Manufacturing and water and waste	Chemicals, plastics and rubber, wood, ash, metallic, non-metallic, organic, waste heat and steam, water and wastewater, and others		telephone calls, interviews and site visits, discussions and brainstorming sessions, geographic information system maps	2001	[60]
	Texas		Manufacturing and water and waste	Commercial, industrial, and municipal waste		Questionnaire survey, modified total design method	2005	[117]
	Pittsburgh		Manufacturing and construction	Ash and others		Highway density map, road density. and total highway density; optimization analysis; life cycle analysis; transportation cost analysis	2008	[118]
Canada	Ontario		Agriculture, manufacturing, and water and waste	Non-metallic, chemicals, and waste heat and steam		Inputs and outputs analysis	2009	[119]
South America								
Brazil			Agriculture and manufacturing	Organic, ash, and others		Economic evaluation, environmental and social analysis, emergy method	2007	[120]
	Norte Fluminense region	14	Agriculture, manufacturing, energy, and water and waste	Organic, chemicals, waste oil, ash, and others		Interviews and visit; scenario analysis, mass balance, synergy matrix, and material flow analysis; environmental, social, and economic indicators	2018	[121]
Colombia	15 towns	34	Agriculture, manufacturing, energy, water and waste, construction, sale and repair, accommodation and food, and administrative and support service	Wood, plastics and rubber, paper, organic, non-metallic, sludge, water and wastewater, and others	Service sharing	Workshops, observations, surveys, and interviews	2018	[34]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Africa								
Liberia	Konia		Agriculture, manufacturing, and accommodation and food	Organic and others	Fishponds	Interviews, optimization model	2014	[45]
Mauritius			Manufacturing and water and waste	Organic, sludge, metallic, and others		Interviews and framework for adopting industrial symbiosis	2017	[122]
Egypt	Borg El-Arab		Agriculture and manufacturing	Organic, metallic, non-metallic, paper, plastics and rubber, wood, and others		Data from internal unpublished sources	2018	[61]
Oceania								
Australia	New South Wales		Mining, manufacturing, and energy	Chemicals, ash, metallic, and others		Aspen modelling	2012	[123]
	Kwinana	12	Manufacturing, energy, water and waste, and construction	Chemicals and others		Triple bottom-line perspective and preliminary sustainability assessment	2013	[124]

[1] NE: Number of enterprises

The cases compiled here are organised by region, and these are arranged into descending order based on the number of cases studied, i.e., Europe, Asia, North America, South America, Africa, and Oceania. Within each region, the various countries are also listed in descending order based on the number of cases studied, and within each country, the same process was carried out in ascending order based on the date of publication of the article.

In the following sections, the main characteristics of the cases of potential industrial symbiosis, the methods used in the analyses and the main potential benefits of these synergies are analysed and discussed.

3.3.1. Level of Implementation

Similar to industrial ecology and the circular economy, industrial symbiosis can be implemented at three levels: the micro, meso and macro levels [40,125–128]. These are related to the boundaries at which industrial symbiosis relationships develop, i.e., at company (micro) level; between businesses with geographic proximity, such as eco-industrial parks (meso level); and activities that are carried out at regional or national level (macro level). Table 2 illustrates the diversity of potential industrial symbiosis cases, shown in Table 1, for each level of implementation.

Table 2. Distribution of potential industrial symbiosis cases by level of implementation.

Levels of Implementation	Potential Industrial Symbiosis Cases (Refs.)
Meso	Industrial park/eco-industrial park: [75,76,87,91,98,104,110,114]; business park: [81]; local industrial network: [64]; industrial districts (companies with geographical proximity): [67]; nearby companies: [35,36]; clusters: [73,107]
Macro	Region: [43,53,66,80,83,93]; region (residential, industrial, rural dimensions): [11]; city (industrial park and urban area, industrial and urban symbiosis): [9,37,39,106]; municipality: [72]; island: [74,122]; agro-industrial symbiosis: [120]; automotive sector: [63]

3.3.2. Industries Potentially Involved in Industrial Symbiosis

The diversity of economic activities with the potential to become part of an industrial symbiosis network is very wide, as illustrated in Tables 1 and A1. Manufacturing, which comprises activities involving the transformation of materials into new products, is the predominant sector in these cases of potential industrial symbiosis, as shown in Figure 4. This figure represents the distribution by country of all the economic activities involved in the various cases, grouped into sections according to the format established in the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Of the 21 sections defined in ISIC, 16 are relevant to the various cases studied, with manufacturing accounting for 63% of the total occurrences of all sections. Sections such as agriculture, forestry and fishing, electricity and water, and waste management and recycling are also among the most frequently seen.

Within the manufacturing sector, the most frequent economic activities in the cases of potential synergy involve chemical, iron and steel, pulp and paper, construction materials, and wood and wood products. While there are cases in which manufacturing is the only sector in the synergy network, such as the study conducted in the Val di Sangro Industrial Area in Italy [64] or in Achaia in Greece [82], most of the cases involve several different industries within the manufacturing sector and other entities in the network that carry out other types of activity. This diversity of sectors has been highlighted by some authors [18,129] as being very important for the establishment of industrial symbiosis networks, as it widens the opportunities available.

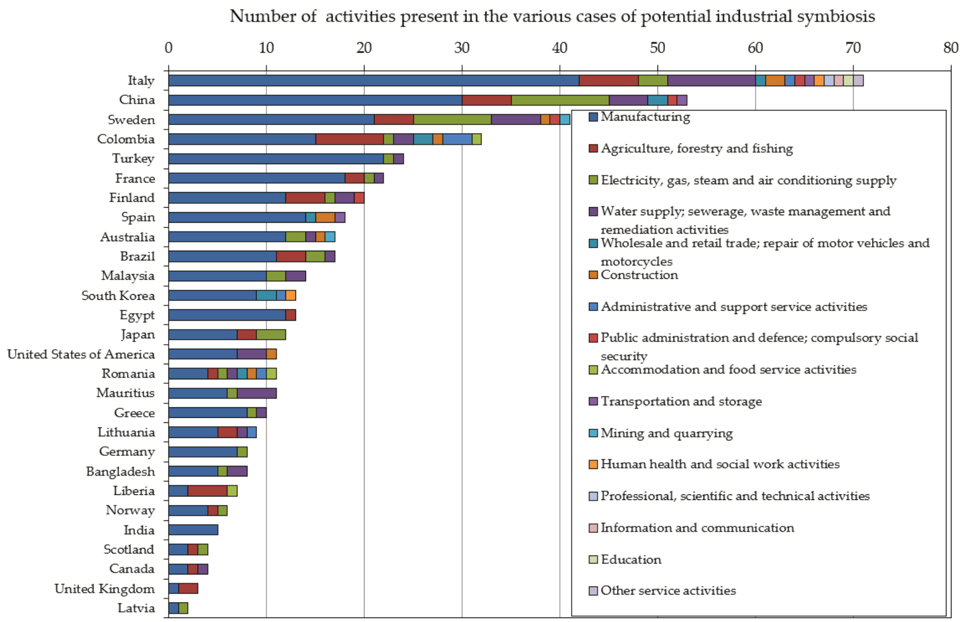

Figure 4. Distribution of the categories of economic activities existing in cases of potential industrial symbiosis by country.

3.3.3. Types of Waste/By-Product Exchange, Infrastructure Sharing, and Joint Provision of Services

The types of waste/by-product that have the potential to be used in the various cases of industrial symbiosis are very diverse, and are directly related to the nature of the economic activities that are carried out in the various networks of potential synergy. The most frequently reported wastes are organic (food and food processing wastes, biomass, livestock and fisheries wastes), plastics and rubber, wood, metallic, waste heat and steam, non-metallic (e.g. glass, waste from construction and demolition, lime-based waste), ash, water and wastewater, chemicals, sludge, and paper.

The sharing of infrastructure and the joint provision of services between companies has also been highlighted as a kind of symbiosis between entities, with potential to be developed and to provide benefits to the participants, albeit in lower numbers than for waste flow. The most frequently mentioned cases are facilities associated with the management and treatment of waste, water and recycling [34,62,64,65,86]. This type of scheme can assist companies in their waste management by freeing them of some of the costs associated with the storage and treatment of waste and by facilitating the direction of waste to various other companies. In addition to these aspects, the sharing of expertise, consultancy, equipment, logistics and transport, energy, and water supply infrastructure have also been identified as having potential to be established. Economic, environmental, and social benefits are identified as being likely to be attained if these types of sharing are established, such as cost savings in the construction of facilities [111], saving of resources used in waste treatment [62], reduction of inefficiencies [64], and job creation [65], and these can serve as drivers for the creation of new symbiosis relationships. Furthermore, the existence of shared and efficient infrastructures can foster new synergies between existing companies in the area and can also be an incentive for new companies to establish themselves in the region with the intention of being part of this symbiosis network. The sharing of services such as transport can also be an important factor in promoting symbiosis networks. Since most of the waste sold does not have a very high commercial value, any reduction in costs such as via the sharing of services can increase the potential economic benefits to the companies involved in these synergies and can foster the creation of new symbiosis relationships.

3.3.4. Methods Used in the Analysis and Assessment of Potential Industrial Symbiosis

In order to identify potential synergy relationships and assess the feasibility of implementing various cases of industrial symbiosis, several methods were used, as listed in Tables 1 and A1. The main objectives of this work were to study the best ways to establish synergy networks with regard to the most potential waste streams and the companies with the highest potential for integration and to assess the potential impacts that industrial symbiosis can have on the environment, the companies involved and the local population.

One of the first steps in the design and analysis of a potential synergy network is the collection of information and quantitative data. Various methods have been used for this, such as interviews [44,65,78,82,106], questionnaires [9,37,63,85,111], site visits [64,84,86,112], and focus groups [53,64,68,85].

To enable the realisation of industrial symbiosis networks, it is also essential to obtain knowledge not only of the possible participants but also of the numbers and types of waste/by-product available. Thus, in addition to meetings with local businesses that help foster possible relationships, as achieved in Emilia-Romagna, Italy [53], the Catania and Siracusa districts in Italy [66], and Colombia [34], the use of digital programs and platforms can also facilitate this interaction by building a common base with potential participants and waste and by optimising possible relationships. Examples of these are the development of a digital web platform for the electrical and electronic equipment sector [38], the Looplocal tool, which is useful in countries with geographically dispersed industries [72], the eSymbiosis multilingual service, implemented as an accessible web service [80], the SymbioSyS tool [87], and the ESOTA®platform, which is based on relationship mimicking [112].

One of the factors that can enhance the realisation of industrial symbiosis relationships is realisation of the potential benefits to businesses, not only the economic benefits, which are essential in encouraging companies to create synergies, but also the environmental and social benefits. While some of the studies carried out only a qualitative analysis, a significant proportion assessed at least one of these benefits. Of the three dimensions of sustainability, the environmental aspect was the most frequently discussed, and the most commonly applied method was the use of environmental indicators [10,13,39,88,105]. The reduction of carbon dioxide emissions was the most frequently addressed in the various analyses [35,36,38,63,70,73,98], followed by quantification of savings in the consumption of resources such as energy, water, raw materials and fossil fuels [9,39,63,88,95], and quantification of the reduction of waste sent to landfills [9,34,39] resulting from the potential application of industrial symbiosis. Life cycle assessment [9,38,63,84,98] was the method most commonly used to assess the environmental impact. The economic aspect, which was the second most frequently assessed, was measured using the life cycle costing method [104] and several metrics that primarily reflected reductions in raw material [39,60], fuel [13,106], energy consumption [35,36], waste disposal costs [38,39], and increased revenue [34,35,38,45,109]. Job creation [45,80,120,121] was the indicator most commonly used to assess the social benefits of realising potential industrial symbiosis relationships. The material flow analysis method [9,10,39,88,111] has also been used several times to quantitatively assess potential industrial symbiosis.

The environmental and economic components of sustainability have also been used to optimise and select the best potential symbiosis relationships. In order to compare industrial symbiosis with an equivalent system in which companies remain separate, several forms of synergy network integration have been evaluated and optimised based on their total costs [69] and carbon dioxide emissions [70] using the MIND method, an optimisation method based on mixed integer linear programming. Three models were developed using mixed integer linear programming to model and optimise waste streams in an industrial park in France with regard to cost and environmental impact [75].

SWOT analysis has also been used several times [67,76,111,114] to study the internal and external factors in the potential application of industrial symbiosis networks.

3.3.5. Potential Environmental, Economic, and Social Benefits

An analysis of the various cases of potential industrial symbiosis leads to the conclusion that most of them intend to achieve environmental, economic and social benefits through these practices. Table 3 gives some examples of this. The environmental component was most frequently measured, largely due to international constraints on reducing greenhouse gas emissions, as well as national constraints on emission reductions and the amount of waste sent to landfills and incinerators. It is therefore important to ascertain whether these practices can be effective in meeting these limitations.

The economic component, which is often cited as a determinant factor in decisions by companies to establish symbiosis relations [34,130], was the second most frequently quantified component of sustainability. However, not all cases of industrial symbiosis have the potential to provide economic benefits to all participants, such as an example of symbiosis in a chemical industrial park in the west of Urumqi City, China. In this case, one of the companies did not receive economic benefits, largely due to the fact that the price of the raw material was lower than some types of industrial solid waste that were used for the production of bricks [130]. The environmental benefits, such as reduced consumption of natural resources and greenhouse gas emissions, justify the implementation of these networks of synergy, even without economic benefits, although, in these cases, it is important that local or national governments provide economic incentives that encourage companies to create these synergies.

It can therefore be concluded that the implementation of these cases of industrial symbiosis can provide a number of environmental, economic, and social benefits that translate into an efficient use of waste and resources.

Table 3. Main environmental, economic and social benefits of potential industrial symbiosis.

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[62]	Improved air quality (emissions reduced up to 65%), water quality (pollution reduced by 20–30 times), water and energy consumption and CO_2 emissions (reduced up to 60%)		
[69]		Reduction in system cost by 17.6%, increase in electricity production by 0.5%, decrease in steam discharge by 78.0%, decrease in waste heat discharge by 80.4%, and increase in bark sales in 72.8% compared to the reference case	
[85]			On-site and off-site jobs creation, contribution to the alleviation of rural fuel poverty
[63]	Reduction of resource depletion, air emissions, and landfilled wastes	Costs of secondary polypropylene are reduced up to a factor of 10, compared with virgin plastics; reduction of waste costs; reduction of 93% of supply costs	
[73]	Reduction of CO_2 emissions, reduction of the amount of waste that is currently sent to landfill, long-term storage of the CO_2, water savings, and reduction of dependence on petroleum-based materials	Increase of the production, cost reduction, and creation of new sources of income	
[36]	Industrial symbiosis complexes with two and six factories would allow to avoid equivalent CO_2 emissions of approximately 78 kteCO_2/year and 377 kteCO_2/year, respectively	Implementation of a steam exchange system between the two chemical plants and the thermal plant, with a distance of 1.8 km, could reduce the annual heat costs of the plants by approximately 15%, with a payback period ofeight8 years for recovery of infrastructure investment costs	
[34]	Twenty projects would prevent 7207 tons of waste disposal and 1126 tons of greenhouse gas emissions and would reduce energy consumption by 619,500 kWh and water consumption by 146,000 m^3 per year	It is estimated that the 20 projects can generate economic benefits in the amount of approximately $760,000 USD, considering both cost savings and additional revenue; on average, each project was estimated to generate about $38,000 USD, with a three-month payback period	

Table 3. *Cont.*

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[95]	Energy reduction up to 35%, reduction in water consumption up to 50%, and reduction in greenhouse gas (GHG) emissions by 20%	Cost of waste disposal is practically eliminated	
[39]	Save raw material 2.5t and energy 12.25 GJ/t steel; 1t waste plastic could substitute 1.2 t coke; save material of clinker 500 kt/year; reduce slag by 500 kt/y; in total, resource saving and waste reduction reduce the CO_2 emissions by 1028.06 kt-CO_2/y	In terms of raw material saving, fossil fuel saving, and solid waste reduction, cost reduction is 54.14MUSD/y, 13.84MUSD/y and 4.23MUSD/y	
[106]	In the scenario for the total of industrial and urban symbioses, the CO_2 emission could be reduced to 1,108,682 ton CO_2/yr (this reduction of CO_2 emission is approximately 2% of the total CO_2 emissions in Ulsan)	The fuel cost could be reduced to $352.5 million USD/yr	
[120]	Rationalization of land use, avoidance of greenhouse gas emissions and toxic gases, and minimization of the needed inputs and equipment	Liquid present value: $10.93 million USD, economical revenue: 16.29%/year, and return time: 4.6 years	Creation of 241 jobs in the initial phase and more than 5400 in the eight months of harvest, construction of civil and social facilities
[124]	Chemical release due to dust containment avoided, avoidance of release of toxic chemicals to environment and ground water contamination, avoids $CaCl_2$ release to marine environment, less use of virgin resources and less environmental burdens by avoiding nitrogen oxide emissions	Avoid fines from dust emissions, from waste water and from emissions; savings to company and savings in the costs of using less water from other sources; revenue from $CaCl_2$, from the sale of ammonium nitrate, and from SiO_2 sales	Respiratory effects from fine dust avoided; less health risks due to reduced emissions, avoidance of long-term exposure to SiO_2, and avoidance of release of nitrogen oxides

3.4. Cases of Potential Industrial Symbiosis Applied to New Products and New Uses of Waste

Research into new uses for waste and the manufacture of new products based on industrial symbiosis is essential in order to reduce the consumption of raw materials and reduce waste sent to landfills and incineration plants. However, despite the environmental and economic benefits of this reduction, the process of moving from research to practice is not always rapid or, indeed, possible. In addition to the barriers to the creation and development of industrial symbiosis, which are often referred to in the literature, such as a lack of trust among potential collaborators [33,116], the risks and uncertainties associated with the costs and benefits of such synergies [18,131], and a lack of knowledge [34,41], there are other more specific obstacles that impede these new uses. Current legislation restricting the integration of new waste materials into productive processes [132,133] and the toxicity of some of these waste materials [134] are examples of barriers that can hinder the flow of waste materials and thus condition the development of future synergies. Thus, several studies have investigated future relationships of industrial symbiosis with a focus on the use of new waste materials and their reutilisation in the manufacture of existing or new products. Table 4 presents a summary of these studies, and in addition to the location and main characteristics of the industrial symbiosis, describes the methods used in the various studies. The different case studies are grouped into regions, i.e., Europe, Oceania, North America, and South America, which are sorted into descending order in terms of the frequency with which they appear in the studies. In cases with an equal number of articles, the ordering was carried out based on the date of publication, in ascending order.

It can be seen that, although these cases are few in number, a great variety of industries is involved in potential industrial symbiosis, and there is a wide range of different waste materials and potential uses of these in the manufacture of new or existing products. The geographical distribution is also relatively varied, with studies carried out in Europe, North America, South America, and Oceania. Although not all of these studies were contextualised with regard to a specific location, the vast majority studied the potential for using new waste materials within a given geographical context.

Table 4. Potential applications of industrial symbiosis to various products and wastes, and studies analysing these applications.

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
Finland		Bioenergy production and forest products industry waste water treatment	Bio fly ash and bio sludge	Forest fertilizer	Laboratory scale production and test, life cycle assessment	2016	[135]
Finland	Oulu, Raahe and Kemi	Pulp and paper mill, carbon steel plant, mine, and power plant	Lime waste residues, green liquor dregs, steel ladle slags, desulphurization slag, attle rock, bottom ash, fly ash, and paper mill sludge	Soil amendment pellets, low-grade concrete, and mine filler	Life cycle assessment, CML impact assessment method, global warming potential assessment and exergy analysis method, dimensional analysis approach, primary exergy conversion efficiency of the production process	2016	[133]
Greece		Biodiesel plants, agro-industries, lignite-based power generation plant, and agricultural biomass-based combined heat and power plant	Crude glycerol and agricultural biomass	Alternative fuels production	Experiments in a laboratory scale	2016	[136]
United Kingdom	North east of England	Integrated steel mill	Vanadium-bearing steel slags		Semi-structured interviews with industry representatives, industry associations, and consultants	2017	[132]
Wales	Baglan	Foundry and research centre	Platinum from waste thermocouples	Catalytic electrodes suitable for dye-sensitized solar cell production	Synthesis and analysis of chloroplatinic acid samples, fabrication and characterization of platinized counter-electrodes, electrical impedance spectroscopy analysis, chemical analysis, supply and environmental impact analysis, cost-benefit analysis	2018	[137]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
Italy	S. Angeli di Rosora, Marche	Building and automotive sector	Retired lithium-ion electric vehicle batteries	Battery energy storage systems	Experimental tests, simulation of the energy system, integrated load match analysis and life cycle assessment approach, grid interaction indicators	2019	[138]
Australia	Western Australia	Nitric acid plants and fertilizer producer	By-products formed from chemical absorption of nitrogen oxide	Potassium nitrate fertilizer	Life cycle assessment and life cycle inventory; process engineering applications: stoichiometric balances, thermodynamic properties of chemical reactions. and solubility conditions; Australian Environmental Impact method; uncertainty analysis	2016	[139]
Australia	Kwinana	Phosphoric acid manufacture	Phosphogypsum	Paper and fertilizer	Life cycle assessment and life cycle inventory; economic and social analysis; Economic Analyzer software; sensitivity analysis; indicators for social implications assessment: employment opportunity, intergenerational social equity, and avoided land use	2018	[140]
USA	Southwest region	Original equipment manufacturer dealership, battery diagnostic centre, and photovoltaic industry	End of life electric vehicles lithium-ion batteries	Storage of renewable energy generated through photovoltaic technology	Avoided environmental impacts for reusing degraded electric vehicles batteries and tool for reduction and assessment of chemicals and other environmental impact	2019	[141]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
USA		Automobile industry and building and construction industry	Waste steel scrap	Metal facade systems for buildings' exteriors	Required capital cost and required energy consumption for making a new metal building facade product by recycling and by directly reusing waste steel scrap; potential capital cost savings and energy consumption savings by reusing waste steel scrap when compared with recycling	2019	[142]
Brazil	Quadrilátero Ferrífero, Minas Gerais	Iron mining and steel, and brick manufacturing industry	Steel slag and iron ore tailings	Solid brick	Evaluation of chemical composition of the samples by energy dispersive X-ray spectroscopy, expansibility test using the method defined in Brazilian Standard ABNT NBR NM 13, experimental procedures, visual analysis, mechanical tests, comparative evaluation, QE-CO_2 method	2018	[143]
			Wastes from laptop and photovoltaic system		Design measures and technological, environmental, and economic implications analysis	2012	[144]
		Cement industry and municipal solid waste management	Energy-from-waste air pollution control residues (fly ash and calcium or sodium salts from scrubbing of acid gases)	Blended cements	Analysis of pH-dependent leachability of pollutants from granular material and diffusion-controlled leaching from monolithic specimens; laboratory investigation of eight EfW APC residues	2014	[134]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
		Winery and environmental industries	Grape marc	Bioadsorbent for the desalination of water containing copper (II) sulfate	Elemental analysis, preliminary adsorption experiments, experimental design for establishing the optima conditions to remove copper(ii), quantification of copper(ii) through a spectrophotometric analysis, quantification of adsorbent capacity and percentage of copper removal, X-ray diffraction analysis, statistical analysis—response surface method, and multiple regressions using the least squares method	2018	[145]

In some cases, geographical location was not constraining, and the use of certain waste materials could be transferred to several locations. For example, waste materials from common industries and those available in most countries can be used to extend the range of application of industrial symbiosis. One example of this is a case study of the production of potential symbiosis products such as soil amelioration pellets, low-competence concrete, and mine filler from a mixture of waste materials from multiple industries, such as pulp and paper mills, carbon steel plants, mines, and power plants [133]. Although this was studied in the context of Finland, this symbiosis could be replicated in numerous different locations due to the nature of the industries available. Another example was a study of the use of wine grape pulp to produce a bio-adsorbent for the removal of copper sulphate from water [145]; this symbiosis between the winery and environmental industries could also be reproduced in several distinct locations.

In other cases, however, geographical location can condition or incentivise the use of certain waste materials in the symbiotic process. For example, the strong presence of a particular type of industry can be an enhancer for industrial symbiosis and the search for new solutions to the waste generated by the production process. One example is the pulp and paper industry, which has a long tradition in Finland and is responsible for large volumes of production [21] and consequently high levels of waste generation. One of the studies focused on the potential uses of sludge resulting from the processes of wastewater treatment in the forestry industry and of fly ash resulting from the production of bioenergy for the production of a forest fertiliser [135]. In Brazil, the steel, mining, and construction sectors have a strong presence and are responsible for large-scale generation of waste and greenhouse gas emissions, and this has boosted the search for sustainable solutions. Thus, new solutions for the use of iron and steel mining waste were studied as an example of potential symbiosis in the production of solid brick/construction blocks in the Quadrilátero Ferrífero zone [143].

Current progress and the consequent emergence of new products have created new streams of waste, and with them the need to provide solutions which promote a more sustainable end of life. If these wastes result from or are integrated into a sector or product that has a significant environmental impact over its life cycle or a certain part of it, industrial symbiosis makes it possible to reduce the environmental impact of this sector or product. One of the examples found in the literature was the potential use of end-of-life electric vehicle lithium-ion batteries as storage systems for the renewable energy produced from photovoltaic systems in the generation of electricity for buildings [138,141]. In addition to using a waste material that is expected to increase over the next few years, this potential synergy also contributes to the reduction of carbon dioxide emissions from two sectors that are responsible for high greenhouse gas emissions—buildings and the automotive sector.

The study of new solutions based on industrial symbiosis is not only due to the inherent characteristics of certain waste materials, such as their toxicity and associated value, but also to the fact that the recycling process is often expensive and a large consumer of energy, meaning that it is not a viable solution. In the case of retrieval of valuable metals such as platinum, the recovered value sometimes does not cover the costs inherent in retrieval [137] if these are present in low concentrations, and industrial symbiosis can address this limitation. One example is a case study of Baglan, South Wales, in which, due to the local proximity between the stakeholders of potential synergy, the recovery of platinum for the production of catalytic electrodes for dye-sensitised solar cells could be translated into environmental, economic, and social benefits [137]. The potential direct use of sheet metal scrap from the automobile industry in the manufacture of new facade systems for the exterior of buildings could also lead to a reduction in costs of approximately 40% and a reduction in energy consumption of approximately 67% compared to a conventional recycling process [142].

All these studies were supported by several methods with different objectives. Since the main aim of these publications was to promote the use of new waste materials or the production of new products empowered by industrial symbiosis, it is not surprising that the predominant methods were those associated with laboratory-scale experiments. These tests were carried out to study not only the characteristics of waste materials [137,138] but also the final products [135,143] in order to guarantee their functionality and suitability for these purposes. A knowledge of the potential environmental, economic and social benefits that these new uses of waste can provide is also very relevant, as these can drive realisation. In the same way as for studies of potential industrial symbiosis between companies, the environmental component was the most frequently analysed aspect [135,138–140], followed by economic factors [137,140,142,144], and finally social components [140]. The potential benefits from the use of new waste materials and the manufacture of new products based on industrial symbiosis are extremely diverse. Table 5 lists the main environmental, economic, and social benefits that could be achieved if some of these potential symbioses were put into practice.

Table 5. Main environmental, economic, and social benefits of the potential use of waste and products through industrial symbiosis.

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[135]	Reduction of global warming potential (GWP) by 99%: production of 1000 kg of potential symbiosis granules would produce GWP burdens of 11.75 kg CO_2-equiv. and the existing NPK-fertilizers produced a GWP burden of 1304.92 kg CO_2-equiv.		
[139]	Reduce the overall GWP, acidification potential and eutrophication potential per kg KNO_3 produced by 7.8 kg of CO_2-e, 0.122 kg SO_2-e and 0.075 kg PO_4 -e respectively in comparison to the production of conventional KNO_3 fertilizer and could reduce GHG emissions by 45%		
[142]		Reusing the sheet metal scrap over conventional recycling of the same material would lead to a cost reduction of approximately 40% ($400 USD/ton) and savings of approximately 67% (10,000 MJ/ton) of energy consumption	
[136]	Provide a rather short-term solution to the existing environmental problem of waste glycerol, contributes to increase sustainability and reduce environmental footprint	Decrease in the cost of biodiesel production	
[132]	Removal of elements of environmental risk, such as vanadium	Income from the sale of recovered metals	
[137]	Per year, divert ~50 g of platinum from landfill, avoid up to 1400 kg of CO_2 emissions associated with primary production of an equivalent quantity of platinum, and give enough platinum to produce catalytic electrodes for ~500 m^2 of dye-sensitized solar cells, which could supply clean energy for 12 homes in the locality (South Wales)	Provide 63% materials cost savings for electrode preparation in comparison to purchasing commercially available chloroplatinic acid hydrate	Provide ~5 days employment

Table 5. *Cont.*

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[140]	Reduce solid waste associated with traditional paper production, where the average amount of solid waste reduction from studied options is 0.01 kg/kg of paper, reduction of contamination of underground water sources or land from leaching of the phosphogypsum (PG) constituents	PG recycling is expected to reduce approximately 12,000 m^2 of land used for stockpiling of PG (based on the average annual operation of the plant of 25,000 tons of PG), which could be reutilized for other economic benefits such as expansion of the industrial plant or be sold for revenue generation	Employment opportunities for people in the surrounding areas; it is expected that 18 job opportunities will be needed
[143]	Reduction in GHG emissions. The construction of the 126,000 households using the T2 brick would generate a reduction of 465,588.9 tons of CO_2, when compared to the concrete block	The carbon credits related to CO_2 reduction in the simulated venture could be traded for $4.3 million USD	Access to lower-cost housing

4. Drivers and Barriers to the Realisation of Potential Industrial Symbiosis and Strategies to Overcome These Barriers

A knowledge of the drivers and barriers to the implementation of industrial symbiosis is essential in order to develop measures that enhance the application of this practice. Based on the studies of potential industrial symbiosis analysed above, this section compiles the various drivers, i.e., factors that promote and facilitate the development of industrial symbiosis, and barriers, i.e., the factors that hinder the implementation of this practice. Selected strategies for overcoming the various barriers are also highlighted, as these can create conditions for the various cases of potential industrial symbiosis to materialise.

4.1. Drivers and Enablers of the Realisation of Potential Industrial Symbiosis

An analysis of the articles on potential industrial symbiosis leads to the conclusion that there are a number of factors that play important roles in the realisation of industrial symbiosis relationships. Knowing the environmental, economic and social benefits that this practice provides is important in promoting the creation of synergy networks [146]; however, these are not always the main drivers of this practice, and many other drivers have been identified in studies of potential industrial symbiosis as being conducive for companies to participate in symbiosis networks. In most cases, it is not one factor but a set of factors that create favourable conditions for the development of symbiosis.

The economic, environmental, political, and social context of a country can be decisive in the way sustainability issues are addressed and consequently in how they can favour or condition the development of industrial symbiosis. The distribution of a number of potential industrial symbiosis articles by country, as illustrated in Figure 3, reflects the characteristic context of each country.

Existing legislation, plans and policies in each country are also repeatedly referred to as drivers of industrial symbiosis [82,101,115,118,120]. Companies are encouraged to set up synergy networks through imposing limits on emission or waste disposal through regulations and taxation, facilitating the use of waste, and allocating funds.

The higher numbers of studies of potential industrial symbiosis in Europe cannot be dissociated from the efforts that have been undertaken by European countries to reduce greenhouse gas emissions and to promote the more efficient use of resources. These efforts have been driven by the European Commission, which has established a number of directives, communications and programs with the provision of funds. One example is the "Roadmap to a Resource Efficient Europe" communication, which proposed a framework for action to ensure the sustainable management of all resources without sacrificing economic growth [147]. Another example is the communication "Closing the loop—An EU action plan for the Circular Economy". This communication underlined the importance of industrial symbiosis and proposed to facilitate this practice through cooperation with the Member States, guaranteed funding through cohesion policy funds, and the research and innovation framework program Horizon 2020 [148]. Another initiative launched by the European Commission was Directive 2018/851 on waste; in addition to highlighting the great advantages of improving the efficiency of waste management and recognising waste as a resource, this acknowledges the importance of industrial symbiosis and encourages Member States to take steps to facilitate it [149].

The European countries for which the highest numbers of cases of potential industrial symbiosis have been published are Italy, Sweden, and Finland. All of these countries have common factors that may have contributed to fostering the study of new industrial symbiosis relationships and their implementation, such as (i) a greater concern with environmental issues and the search for sustainable solutions, (ii) the established existence of cases of industrial symbiosis over several years, (iii) a considerable number of cases of self-organised symbiosis networks, (iv) the existence of facilitators through national agencies or local governments, and (v) more stringent environmental regulations [18,21,41,150,151].

The realisation of two cases of industrial symbiosis, involving the automotive [64] and agri-food [65] industries in the Italian Region of Abruzzo, is another example of the combination of several factors in realising the potential of symbiosis. In this case, good communication routes, favourable geographical positions, stakeholder involvement, and the facilitating role of the president of Consorzio Italiano Subfornitura Impresa (CISI) in the case of the automotive industry were viewed as driving factors in the development of industrial symbiosis [152].

China has the highest number of published cases of industrial symbiosis [19] and potential such cases. This may be associated with a set of measures that China has implemented over recent years, such as the implementation of policies and plans, financial incentives, and research incentives. These measures have attempted to contain the negative effects of increasing industrialisation and urbanisation in recent years [153,154], such as increased carbon dioxide emissions [153,155,156], increased amounts of industrial solid waste [154,157], and increasing resource consumption [39,97]. The National Pilot Circular Economy Zone Programme, launched by the State Environmental Protection Administration in 2001, and the laws that have been applied since 2003 to promote the circular economy, are examples of these measures. While not primarily aimed at promoting industrial symbiosis, they contribute to the spread of this practice by providing increased awareness of the importance of resource reuse and recognition of the fundamental role of the circular economy in China's development [23,24]. The China National Eco-Industrial Demonstration Programme launched in 2000 by the State Environmental Protection Administration [25] has also contributed to the increase in the number of potential industrial symbiosis cases and China's leadership in the publication of case studies [19]. This programme has enabled the development of the largest national network of eco-industrial parks, in which industrial symbiosis practices have been promoted [158,159].

The predominance of certain types of industry within countries can also be a driving factor for the creation of industrial symbiosis networks. This is particularly true if they are large consumers of resources and emitters of greenhouse gases, such as the steel and iron industry in China [97,160], and if they play a key role in economic development, such as the agri-food industry in Italy [65] and the iron, steel, and cement industries in China [160,161]. Moreover, these industries have a longstanding tradition in these countries and are located in industrially mature areas, which Jensen et al. [92] have shown to facilitate industrial symbiosis.

A diversity of industries has also frequently been highlighted as conducive to the establishment of industrial symbiosis relationships [76,114], since this opens up a range of opportunities due to the variety of wastes and the numbers of companies that produce them and have the potential to incorporate them into their processes. If there are several companies carrying out the same type of economic activity, this can be an added advantage, since it ensures a more constant flow of waste [77], while if there are no other companies nearby to ensure the incorporation of these wastes into their processes, the viability of industrial symbiosis is compromised. The fact that there are several industries carrying out the same type of economic activity may also enhance other synergies, such as infrastructure sharing and the joint provision of services.

If a company can function as an anchor tenant, this can be an important factor in driving the realisation of industrial symbiosis relationships [76,82,91,93,114]. These companies are able to attract and anchor a network of companies, not only in terms of the supply of materials but also the reuse of waste. There are some examples of such cases reported in the literature, such as a power plant in Honolulu in the US [162], mining firms in Gujiao, China [163], and a pulp and paper mill in Kouvola, Finland [164].

Although not an indispensable requirement for establishing the synergy network, geographical proximity between the potential participants in industrial symbiosis is often referred to as a facilitator [11,36,82,91]. Establishing symbiosis networks with nearby companies can increase trust in the relationship. In addition, the fact that waste is mostly of low economic value, transportation and environmental costs may no longer compensate for the symbiosis connection over long distances.

The existence of industrial symbiosis networks that have already been established in a given place can be a driving force for creating new synergy linkages and extending the network to new companies, since the internal structures [114] and trust relationships that facilitate this development [40] are already established. In addition, there is evidence that these networks can be of benefit to the parties involved, not only in terms of the reduction of waste treatment and landfill costs, but also in terms of the savings made in the acquisition of raw materials, and profits from the sales of waste. If there are entities that can support and facilitate existing on-site cases of industrial symbiosis, these can also act as enablers for the creation of new connections. This role can be played either by public entities such as local governments or by private entities such as business associations [18,41]. These entities, which are aware of the reality of the site, can more easily identify new partners for infrastructure sharing and joint provision of services, as well as new companies that may be able to use waste that is not yet in use, or that can provide waste to companies already involved in industrial symbiosis. However, in places where no synergy networks have been established, the role of these facilitators can be highly relevant, as mentioned in some of the cases analysed here [60,76,82,107]. They can provide training for companies, facilitate the exchange of information [53], foster cooperation and trust between companies [76], and coordinate and help identify possible symbiosis relationships [107].

4.2. Barriers to the Realisation of Potential Industrial Symbiosis

Despite the recognised environmental, economic and social benefits that industrial symbiosis can provide, there are a number of barriers that hinder its development. The literature review shows that these barriers can be of various types, such as economic, technical, regulatory/legal, organisational, social, and cultural [18,33,47,131,165]. By analysing selected publications on potential industrial symbiosis, it was possible to identify several of these barriers.

Several studies of potential industrial symbiosis have pointed out the lack of appropriate policies as a barrier to the application of this practice [53,65,116,122]. Low taxes on landfill disposal [122], a lack of policies that encourage and regulate industrial symbiosis [116], a lack of funds to promote this practice [116], and deficient regulatory frameworks [122] are some of these barriers. In addition, existing legislation may limit the implementation of synergy relationships, especially if it is too rigid, unclear, or inconsistent. One example is Italy's regulatory system, which is referred to in studies of potential industrial symbiosis [53,65] as constraining companies with regard to the use of waste.

There are also others barriers to the creation of industrial symbiosis networks. The first is associated with the reluctance of companies to establish synergistic relationships, not only due to a lack of knowledge of the industrial symbiosis mechanism [116,122] but also due to a lack of knowledge of other companies with the potential to receive or provide waste [9,68]. In addition, a lack of trust [82,116], resistance to providing data on processes and generated waste [122], and uncertainty related to the profitability of the symbiosis network [75] and the associated costs and risks [82] were also identified as barriers to the development of symbiosis relationships.

The fact that companies are implementing measures to reduce waste generation has also been identified as a barrier to the development of industrial symbiosis [68], as there is a concern that the stream of waste involved cannot be guaranteed.

The economic component has been referred to by various authors [18,166,167] as being essential in inducing companies to take the initiative to establish an industrial symbiosis relationship. If the economic value of raw materials is very close to that of waste, there is no incentive for companies to use waste in their production processes [37]. Moreover, the price that companies are willing to pay for waste may not be economically advantageous for the company producing such waste. In this case, there is no incentive for companies to divert waste from landfills and start a symbiosis relationship [68]. In addition to these factors, the role of stakeholders in deciding whether or not to initiate symbiosis relations should be highlighted, as there is often a lack of openness [34] and willingness [116] to initiate this kind of collaboration.

For the establishment of some symbiosis relationships, such as the sharing of waste heat, the initial costs associated with infrastructure are very high, and this makes companies reluctant to establish such symbioses [75,106,107]. A lack of availability of technologies required [9,116] and the high costs of equipment [85] for the realisation of industrial symbiosis have also been identified as inhibiting the realisation of this practice.

The social and economic instability of a country can also condition the establishment of synergies, since although the issue of sustainability is recognised as being important; there may be social issues which take precedence [168]. In addition, the issue of survival is imperative in some countries with developing economies, and since the time between setting up projects and achieving results may often be long in these countries, this may constitute a barrier to the implementation of symbiosis [45].

4.3. Strategies for Overcoming the Barriers to the Realisation of Potential Industrial Symbiosis

Regulations and policies were most often referred to as being important for encouraging or limiting the establishment of industrial symbiosis relationships [85,111,122,169]. While the decision to establish a symbiosis relationship is made by a given entity, the role of policies is critical in encouraging this practice. Thus, in order for these to not function as barriers, it is necessary to provide legislation and policies that are clear, consistent, and less bureaucratic and can facilitate the process of waste use [170].

Economic incentives have also been highlighted as being important in the realisation of industrial symbiosis [9,122]. To create more efficient legislation to facilitate this practice, programmes can be coupled with the provision of funds to promote industrial symbiosis and offer monetary support for companies in terms of the construction of infrastructures or the acquisition of the equipment necessary for the realisation of these relationships [122].

However, even if there are a number of policies and programs that facilitate and encourage companies to establish symbiotic relationships, the companies themselves are often reluctant to make such connections. Thus, to drive the implementation of industrial symbiosis, it is necessary to disseminate information to companies. This can be realised through workshops, working group discussions, and other actions [116,122] that provide the necessary information to companies on industrial symbiosis and its potential benefits. A knowledge of this practice can create the willingness to cooperate, which is fundamental for the realisation of symbiosis networks [68].

The role of facilitators such as local governments and industry associations has also been highlighted as a way to overcome various barriers [34,111], including a lack of confidence, a reluctance of companies to share their data and a fear of relying on other companies. These entities can provide training to various employees on the concept of industrial symbiosis, assist in the creation of trust and cooperation relationships, and help to identify new symbiosis relationships [34,165].

Some barriers such as a lack of knowledge of companies with potential to start symbiosis relationships and lack of trust can be overcome using digital platforms and programs [87]. These tools can enable social interaction between companies and facilitate a search for companies that can provide or receive waste. In addition, where appropriate, they can facilitate the choice of the best option based on prices, distances and potential environmental and economic benefits [38,80,87].

In order to overcome the barriers associated with a lack of available technology, there is a need for increased investment by governments in research and development into technological innovations and greater involvement with research teams from university or business associations [9,37].

In the case of poorer countries with social problems such as high unemployment rates, low incomes, illiteracy, or low life expectancy, such as the cases studied in the Philippines, Liberia, India, and Bangladesh, the implementation of industrial symbiosis practices is more difficult. However, when properly supported, the implementation of this practice can make a positive contribution to the long-term sustainable development of these countries, as it makes it possible to combine environmental and economic issues with social aspects. These advantages translate into job creation, long-term links between companies and the possibility of small businesses entering the synergy network [45,61,171]. It is therefore essential to support these countries in the development of industrial symbiosis. Several authors have proposed measures for overcoming the characteristic barriers in these countries, such as (i) extending the symbiosis network to other stakeholders such as community leaders and government organisations [45], (ii) the establishment of policies that encourage symbiotic relationships between small businesses, such as small farms [45], (iii) the provision of subsidies [122], and (iv) helping to obtain international support created specifically for sustainable projects in developing countries [122].

The main drivers and barriers to achieving potential industrial symbiosis are very diverse, as illustrated in Figure 5, and overcoming the various barriers and achieving further dissemination of industrial symbiosis requires concerted action at various levels. It is therefore essential to coordinate the various entities and resources and to restructure existing regulatory systems. It is also necessary to support companies in paradigm shifting and raising awareness of the advantages of more sustainable practices, and in particular industrial symbiosis.

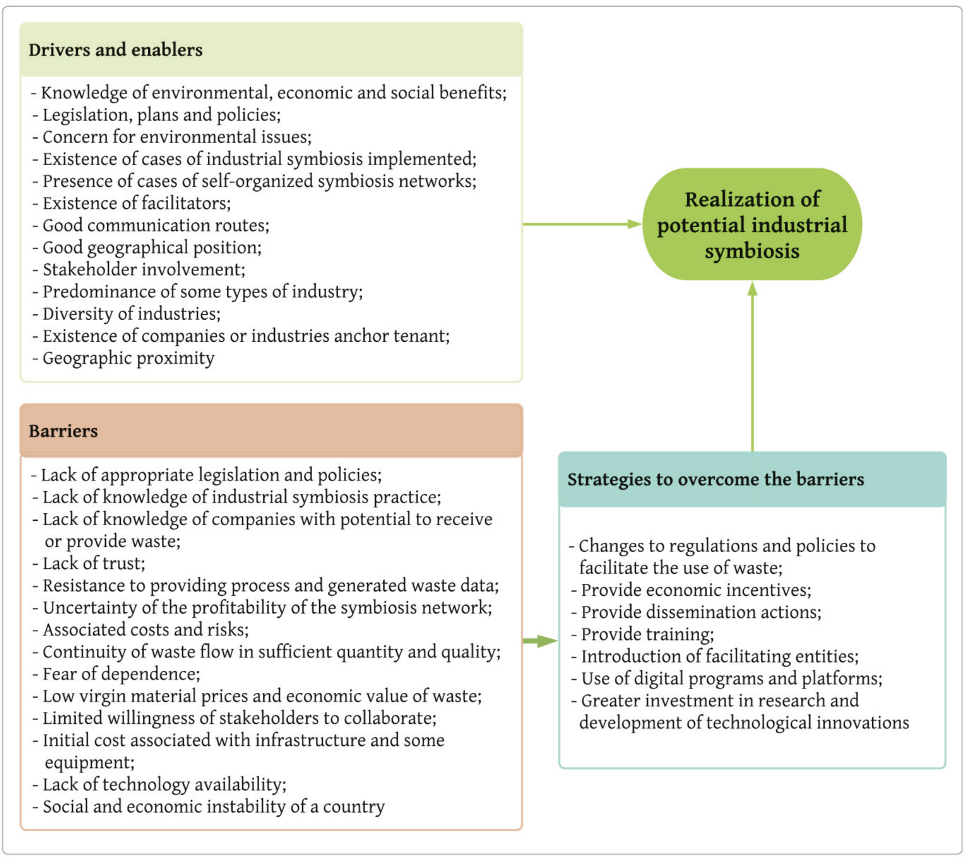

Figure 5. Key drivers, enablers, and barriers to the realisation of potential industrial symbiosis, and strategies to overcoming these barriers.

5. Conclusions

Despite the large number of existing cases of industrial symbiosis, there is still huge scope for growth, as evidenced by the various studies that have been carried out to assess the potential application of this practice. A comprehensive review of the literature reveals that there is potential for the development of new industrial symbiosis relationships around the world, with a wide diversity in terms of network size, the types of economic activities involved and the types of waste stream.

Most existing studies focus on countries where symbiosis is already widely applied, such as China, Sweden, Finland, and the US. However, the potential for industrial symbiosis has also been studied in countries where this practice has few or no existing cases, such as Egypt, the Philippines, and Colombia. Although most of these cases reproduce existing symbiosis relationships with regard to the activities and types of waste involved, there have been studies that have looked into the potential use of new waste and the manufacture of new products based on industrial symbiosis relationships. Furthermore, the potential for applying industrial symbiosis is not limited to replacing resources with waste; there are also many opportunities for other types of synergies, such as infrastructure sharing and joint provision of services.

Despite this great potential, it was only possible to verify the realisation of two of the cases of potential industrial symbiosis in the literature review. It can be inferred that there was either no interest from industry in the implementation of industrial symbiosis or, if the potential was realised, there was no follow-up that resulted in a publication. However, it is important to understand that there is interest from industry in implementing these cases. Some of the studies have a more theoretical character, and many of them resorted to interviews and site visits, which implies that industry is aware of the potential for industrial symbiosis. Thus, it is important to monitor the implementation of symbiosis in order to better understand the dynamics of implementation of this practice and the main factors enhancing its development. If potential cases of industrial symbiosis are not realised, it is relevant to analyse with companies the main barriers to this implementation.

The work carried out in this paper regarding knowledge of the potential for industrial symbiosis and the main barriers and drivers to its implementation may have theoretical implications. The characterisation of the various cases can contribute positively to the research efforts that have been developed to increase the application and diffusion of industrial symbiosis. Knowledge of the main drivers and barriers may also have implications for the development of theory, in terms of an understanding of industrial symbiosis and the main mechanisms that can drive or hinder it.

While an effort was made to ensure that the review of the bibliography was as comprehensive as possible, we limited our search to articles written in English and using only research articles, conference articles, book chapters and editorials, and this may have overlooked some cases of potential industrial symbiosis that could provide a greater understanding of this topic.

Of the various types of resource sharing available, most studies address the potential use of waste and the advantages that arise from its integration as a raw material in the production process. However, in future research, it is important to examine more case studies assessing the potential of infrastructure sharing, the joint provision of services, and the potential benefits to the companies, environment, and society. It will also be important to focus on the most favourable conditions and the factors determining implementation of symbiosis.

Future research could also assess whether various cases of potential industrial symbiosis have been implemented in order to increase our understanding of the mechanisms that drive or condition the creation of synergies and thereby promote the growth of industrial symbiosis initiatives.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Potential industrial symbiosis applications and studies analysing these applications.

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Europe				
Italy	Murano, Venetian Lagoon		Glass-based industry	Oxygen	Water treatment	BATTER tool; direct measurements at single installations, mass flow estimations, total amount of air pollutants emitted, technical options score, and evaporation treatment costs for a single water treatment plant	2007	[62]
Italy	Brancaccio, Carini, and Termini Imerese		Automotive sector and neighbouring companies	Plastic sub products and scraps		Questionnaire data survey to organizations and interviews, life cycle assessment	2010	[63]
Italy	Val di Sangro Industrial Area, Abruzzo Region	19	Motorcycle industry		Collective management of scraps: pre-treatment centre and on-site management of the end-of-life of products manufactured by the industrial network	On-site data collection, performed by using semi-structured questionnaires, direct, and e-mail interviews of the leaders, site visits, and focus groups	2014	[64]
Italy	Fucino upland, Abruzzo Region		Agri-food companies, paper mill, PVC sewer pipes producer company, pellets and plywood panels producer company	Paper and cardboard wastes, plastic wastes, and wood wastes	Common local recycling platform	On-site survey; face-to-face non-structured interviews with the head of the provincial Association of Agricultural Producers and semi-structured interviews with the technical staff by telephone or e-mail	2015	[65]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Italy	Emilia-Romagna		Agrofood sector, industries with the technologies able to transform and enhance the by-products, and companies reusing by-products	Agro-food waste, mud, packaging, waste from construction and demolition, textile waste, waste from petroleum refining and natural gas purification, waste from wood processing, and digested		Interviews with private companies and public administrators, guided collective discussion, visits to laboratories, and conferences	2015	[53]
Italy	Catania and Siracusa districts, Sicily		Agriculture, forestry and fishing, manufacturing, electricity, gas, steam and air conditioning supply, water supply; sewerage, waste management and remediation activities, construction, wholesale and retail trade, repair of motor vehicles and motorcycles, transportation and storage, information and communication, professional, scientific and technical activities, administrative and support service activities, education, human health and social work activities, and other service activities	Water, fuels, materials from agriculture, electrical and electronic compounds, municipal wastewater treatment sludge, industrial sludge, packaging, wood and wood products, metals and metal products, construction minerals, industrial minerals, mineral waste oils, plastics and plastic products, foodstuffs, inorganic chemicals, organic chemicals, products from livestock and fisheries, construction, demolition, excavation materials, paper and paperboard, sands from separation processes, glass and glass products	Energy, equipment, expertise, consultancy and services, logistics and transportation	Invitation emails and phone calls; meeting tables	2016	[66]
Italy	Brescia	12	Multi-utility company, steelmakers, cement producer, waste treatment and biomass power station, woodchips producer, car fluff treatment, asphalt producer, caviar producer, the municipality and public service facilities	Black slag, car fluff, dust, mill scales, pallets and waste wood, sludge, and energy (electrical and thermal)		SWOT analysis	2017	[67]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Italy	Brescia	2	Energy-intensive factory (with forging processes), and greenhouse horticulture installations	Carbon dioxide emissions		Economic model: increase of revenues due to the CO_2 enrichment process, savings due to the reduction of CO_2 emissions in the industrial installation, and savings due to avoided natural gas consumptions (used in traditional CO_2 enrichment methods)	2018	[35]
Italy	Province of Pescara, Abruzzo Region		Crop/vegetable production, cattle breeding, greenhouses, fish farming, industrial processing, production of pellets, urban furniture production, road works company, residential system, and waste and energy system (thermal treatment plant, composting, biofuels production, recovery and recycling activities, biomass/biogas energy plant, and wastewater treatment)	Vegetable wastes, plant waste, vegetable waste (dry fraction, e.g. from pruning, sawdust), differentiated residential waste (aluminium, steel, glass, paper, plastics), construction and demolition waste, heat waste, hot water or steam, wastewater, and industrial waste		Qualitative analysis of the scientific literature and secondary data and critical analysis	2017	[11]
Italy	Marche Region	3	Waste electrical and electronic equipment treatment centre, material recycler and a compound producer	Plastics from electrical cables insulation		Web platform. Economic assessments. Life cycle assessment methodology	2018	[38]
Sweden	Small town in southern Sweden		Sawmill, paper mill, paper processing industry, local energy service company, the municipality, ecocycle company, and local waste management company	Waste heat, sawdust, bark, woodchips, ashes, sewage sludge, organic waste materials, paper residues, and fibre residues		Conversational and open-ended interviews and group discussion, direct observation and participation at the sites, mass and heat balances over the system	2005	[68]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden		4	Chemical pulp mill, sawmill, biofuel upgrading plant, and district heating system			Method for analysis of industrial energy systems (MIND method), based on mixed integer linear programming	2008	[69]
Sweden		4	Chemical pulp mill, sawmill, biofuel upgrading plant and district heating system	Bark, steam, heat, chips, and sawdust		Method for analysis of industrial energy systems (MIND method) based on mixed integer linear programming. Commercial optimization solver (CPLEX). Assessment of CO_2 emissions from biofuel and electricity for different accounting models (marginal coal, marginal new technology and average Swedish production)	2008	[70]
Sweden	Luleå, Borlänge, Finspång, Sandviken		Iron and steel industry (integrated steel plant and scrap-based steel plant), pulp and paper industries, district heating consumers, and district heating distributor	Excess heat and gasified biomass residues		System perspective evaluation	2011	[71]
Sweden	All 290 municipalities		Agriculture, forestry, and fishing; mining and quarrying; manufacturing; electricity, gas, steam and air conditioning supply; water supply; sewerage, waste management and remediation activities; and construction			Looplocal method, life cycle inventory	2015	[72]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden	Västra Götaland		Waste incinerators, steel mill, cement industry, manufacture of concrete products industries, polymer industry, algae production, power stations, refineries, paper and pulp industry, municipal and industrial wastewater treatment plants, biogas upgrading plants, greenhouse operator, and methanol production unit	CO_2, fly ash, bottom ash, steel slag, municipal solid waste ash, wastewater, and hydrogen		Top-down approach with three consecutive steps: generic matrix of CO_2 sources, generic matrix of CO_2 receivers, and matching the sources with the receivers at regional level	2017	[73]
France	Territoire de la Côte Ouest, Réunion Island		Agricultural activities, fertilizer production facility, market gardeners, and complementation and granulation factory	Livestock wastes (pig manure, droppings from broiler chickens, and laying hens) and shredded green waste		'Follow the Technology' method and Companion Modelling or Commod	2017	[74]
France		7		Waste/unused energy		Mixed integer linear programming; single objective model to minimize the total cost, single objective model to minimize the total environmental impact and bi-objective model to minimize the total cost and total environmental impact; direct method to quantify the heat energy of firms; key process indicators: demand satisfaction, weighted demand satisfaction, supply utilization, and carbon tax reduction; uncertainty evaluation using sensitivity analysis; multi-objective model and Pareto front analysis; weighted sum method	2018	[75]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
France	Gravelines, Penly, Fessenheim, Tricastin, St Alban, Nogent sur Seine, Civaux, St Laurent des Eaux, Bugey, Chinon, Blayais, Chooz, Cattenom, Flamanville, Paluel, Golfech		Nuclear plants, agri-food industries (fruit and vegetables, dairy products, starch products, sugar refinery and malt production), wood, pulp and paper (wood panels, pulp and paper, card and paper and corrugated card), chemical and pharmaceutical industries (dyes and pigments, other basic organic chemicals and basic pharmaceutical products) and plastic, rubber and other elastomers (basic plastic materials and synthetic rubber)	Steam		Average energy intensity in a subsector, production value, average heat consumption of a factory in a subsector, and heat consumed by a factory in a subsector; spatial mapping methods and geographical information system; techno-economic model: energy consumption sub-model (maximum thermal power required), energy generation sub-model (infrastructure cost of a combined heat and power upgrade, required cost, and additional CO_2 emissions to compensate for power generation losses), and energy distribution sub-model (pipe diameter, heat loss assessment, pumping cost, CO_2 assessment, pipeline installation cost, and annual rental cost); linear programming problem	2018	[36]
France	Salaise-sur-Sanne and Sablons		Chemical, recycling and raw material transformation, and urban areas	Industrial waste	Shared infrastructures (for energy supply, cogeneration, solid waste treatment, reclaimed water, etc.)	SWOT analysis	2018	[76]
Finland	Oulu		Steel, pulp and paper industry, cement products manufacturer, soil amendment, soil fertilization, and pellets/ameliorants manufacturers	Granulated blast furnace slag, ashes, fibre clay, and alkaline residues		Literature review and study of a spectrum of residue-based product concepts for further research	2010	[77]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Finland			Waste management, wastewater treatment, municipality, biogas producer, crop farm, and animal farm	Sewage sludge, manure, organic household waste, and digestate		Interviews with companies, collaborative research approach, replication approach	2015	[78]
Finland			Horse industry, agriculture and pellet production industry	Horse manure		Survey sent to companies	2018	[79]
Greece	Viotia		Aluminium casting company, and companies which have capacities to buy and use aluminium waste	Aluminium waste		Ontology engineering approach—eSymbiosis. Metrics for industrial symbiosis benefits: Economic: cost savings to business, and additional sales to business; Environmental: landfill diversion, CO_2 reduction, virgin raw materials saved, hazardous waste eliminated, and water savings; Social: jobs created, and jobs saved	2015	[80]
Greece	Pili		Power plant, furniture manufactures, sewage treatment plant, concrete industry, and food industries	Sawdust, ash, whey of cheese dairies, and salad residues	Utility sharing: autonomous water supply system	Methodology proposed and implemented to determine the most appropriate location and bioclimatic criteria	2017	[81]
Greece	Achaia		Olive-oil production facility, biopolymers (PHAs) production facility, and plastics production facility	Olive mill wastewater and PHAs		Telephone interviews, visits, and face-to-face interviews	2017	[82]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Germany	Rhine–Neckar				Network structure, waste management software, waste analyser software, and intranet platform	On-site surveys	2004	[83]
Germany	Central Germany		(i) Lignocellulosic biorefinery plant, and chipping; (ii) lignocellulosic biorefinery plant, chipping, refinery plant and waste wood–fired CHP units; (iii) lignocellulosic biorefinery plant, waste wood–fired CHP units, refiner plant, chipping, bio-based resins and adhesives, wood panel production, composite manufacturing, and engineered wood products	(i) Beech wood chips from industrial residues; (ii) waste wood, bark residues, and sawmill by-products; (iii) residues from industrial wood		Communications and site visits, life cycle assessment and CML 2013 method, indicator assessment for the CML impact categories and relative advantage or disadvantage of the environmental impact	2018	[84]
Scotland	Perth and Kinross		Sawmill, pellet mill, and combined heat and power plant	Milling wood residues, sawdust, and residual wood fibre		Questionnaires to estate owners, forestry consultants, wood processors and equipment suppliers, and five focus groups with 45 residents	2007	[85]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Scotland	Perth and Kinross		Forest industry, sawmill, combined heat and power plant, and wood pellet mill	Woodchips and sawdust		Questionnaire survey of representatives from the wood fuel supply chain and an attitude survey of a sample of off-mains gas residents	2007	[43]
Spain	Besaya	80	Commerce, repair of motor vehicles and motorcycles, manufacture of basic metals and of fabricated metal products, construction, manufacture of mechanical machinery and equipment, manufacture of paper and paper products, printing and reproduction of recorded media, manufacture of other non-metallic mineral products, other manufacture activities, manufacture of food products, beverages and tobacco products, transport and storage, manufacture of chemicals and chemical products, manufacture of wood and of products of wood and cork, manufacture of rubber and plastic products, and manufacture of transport equipment	Waste oil, used metal containers, used coolants, ink slag, waste sand, rubble and waste material from construction, solid wastes (plastic, discarded tires, wood cuttings and slag from varnishes and paint), waste products from oils and grease (food, machining, hydraulics, motor, separators), lime-based waste products (plasters and slag), waste products from plastic (plastic, shavings and burns), waste products from ferrous metals (ferrous metals, ferrous metal filings and shavings, scrap metal), waste products from glass, waste products from lead batteries, waste products from used tires and slag, waste products from catalysers, waste products from wood without hazardous substances, waste products from ceramic materials (roof tiles, ceramic materials, bricks), waste products from plaster, waste products from cellulose, and waste products from food	Joint waste management: central areas for communal waste storage, shared use of waste storage space, shared transport of waste to municipal management points, joint management of waste products for sale or exchange, joint management of waste by an external agent, and shared use of waste treatment and recovery installations	Questionnaires and visits to various companies	2015	[86]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Spain	Cartes, Cantabria autonomous community	25	Automotive industry, metallurgy and manufacturing, building industry and other various manufacturing industries	Edible oil and fat, paper and cardboard packaging, etc.	Service or infrastructure: common transport and waste collection and waste treatment services	Relational database management system, georeferencing, geographic information systems, and application programming interface; SymbioSyS tool	2017	[87]
Lithuania	Jonava		Nitrogen fertilizers and chemical products manufacturer company, cattle farms, slaughterhouses, municipal wastewater treatment plant, bio-fuel production and/or solid recovered fuel production in pellet form company, administration, and special purpose facilities	Waste heat energy, biodegradable waste (manure and slurry), and sewage sludge		Material flow analysis, material and energy balances of each processes, fuel and energy balances of energy production processes, evaluation of environmental indicators (relative environmental indicators, energy savings, loss of waste heat energy and volume of carbon dioxide emissions) and comparative analysis; feasibility analysis (technical, environmental and economic evaluation)	2016	[88]
Lithuania			Nitrogen fertilizer production company, cattle farms and slaughterhouses	Biodegradable waste		Indicators: geostrategic supply risk and economic importance	2018	[89]
United Kingdom			Bio-refineries, agricultural production, and forestry	Lignocellulose and municipal solid waste (organic food and packaging)			2008	[90]
Norway	Mongstad	6	Refinery plant, coal gasification, combined heat and power plant, production of synthetic transportation fuels, carbon capture and utilization, and aquaculture	CO_2 and waste heat		Mass and energy balance assessment, material and energy flow analysis, carbon and hydrogen flow analysis, CO_2 emission evaluation, and sensitivity analysis; hierarchy analysis method	2008	[91]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
England	Thames estuary, Port of Bristol, east Birmingham, Mersey estuary, and Teesside				Utilities-sharing	Habitat Suitability Mapping: Habitat Suitability Index, Geographic Information System model, Symbiosis Suitability Index, Symbiosis Suitability Map, Symbiosis Suitability Index Variables and Variable Aggregation, and Multi-Criteria-Evaluation mapping. Sensitivity analysis	2012	[92]
Finland and Sweden	Gulf of Bothnia	7	Carbon steel mills, stainless steel mill, zinc plant, and iron regeneration plant	Iron and zinc dusts and scales, jarosite, direct reduced iron, zinc oxide, and manganese dregs		Strengths and weaknesses assessment in national and European Union waste regulation and common pool resource management analysis	2012	[93]
Latvia		2	Brewery and biogas plant	Brewer's spent grain		Site visits. Cumulative intensity indicator of a considered factor (energy consumption and CO_2 emission generation)	2015	[94]
European country			Sugar-beet production, microalgae cultivations, and agro-energy sector	CO_2 and water effluents		Concept analysis	2015	[95]
Romania	Botosani and Neamt		Manufacture of profiles and fittings from steel, manufacture of ceramic sanitary fixtures, institutions and small businesses (tourist pensions, offices, kindergartens, etc.), construction of residential and non-residential buildings, supply of steam and air conditioning, manufacture of garments, manufacture of furniture, agriculture, collection, purification and distribution of water, and retail sale of audio/video equipment in specialized stores	Hot gas	Infrastructure for utilities and supply process optimization	Interviews with the board, or the manager, of each company	2017	[44]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Asia				
China	Handan		Heavy chemical industry, cement industry, coal chemical industry, iron and steel industries, building materials factory, power plant, agricultural production, aquaculture, and urban heating	Fly ash, grey water, coal gangue, PVC profile processing waste, waste water, waste heat, and steel slag			2009	[96]
China	Shanghai City and Jiangsu Province		Cement and steel industries, urban areas and industrial sectors	Municipal wastes (plastics and organic wastes) and by-products from industries		Divisia analysis: total output and energy intensity of each sector and "Divisia" index approach; energy demand analysis and regression analysis: regression equations using the Vector Auto-regression model defined for forecasting gross regional product, population, energy consumption, and cement and steel production	2011	[97]
China	Jinqiao		Central heat-supplying company, waste treatment company, enterprises, and wastewater treatment plant	Sewage sludge and used oil		Experiments in a laboratory, life cycle assessment (global warming potential, acidification potential, eutrophication potential and human toxicity air), total environmental impact potential	2011	[98]
China	Yunfu	3	Sulphuric acid industry, chemical enterprise, and power plant	Sulphur acid, residue steam and heat		Production cost and sale revenue analysis	2011	[99]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	Shenyang		Equipment manufacturing industry and logistics industry			Coefficient of industrial agglomeration degree, Space Gini coefficient, and Hector Fanta coefficient of an industry; logistic model. Index of competitive analysis; expert evaluation method; relational degree taxis	2012	[100]
China	Guiyang		Iron/steel industry, cement industry, coal chemical industry, phosphorus chemical industry, aluminium industry, power plants, and commercial and residential area	Steel slag, slag, red mud, waste steel, waste plastics, coal gangue, coal fly ash, and waste heat		Questionnaires. Material flow analysis, environmental benefit evaluation (avoided resource consumption or avoided waste emission due to the symbiotic activity) and CO_2 emission reduction, effects of resource efficiency enhancement, cost reduction	2015	[39]
China	Guiyang		Iron/steel industry, coal chemical industry, phosphorus chemical industry, aluminium industry, cement industry, power plants, and commercial and residential area	Steel slag, slag, red mud, coal gangue, coal fly ash, waste heat, waste steel, and waste plastics		Questionnaires, material/energy flow analysis. Process life cycle assessment, avoided consumptions and emissions for a company, CO_2 emission reduction from the avoided resource or waste in a company, hybrid physical input and monetary output model hybrid life cycle assessment model integrating both process life cycle assessment and input–output model, life cycle emissions change. Scenario analysis.	2016	[9]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	Hangu, Tanggu, and Dagang Districts, Tianjin Municipality		Seawater desalination plant, sea salt production, mariculture, power plant cooling, Artemia culture, bromide extraction, and salt chemical industry	Clarified seawater, concentrated saline, and bittern		Satellite images analysis, geospatial data processing and analysis software, manual visual interpretation, and landscape type classification system	2015	[101]
China	Liuzhou	5	Iron and steel making, power generation, ammonia, carbonate production, cement and construction material manufacturing companies, and communities	Waste plastics recycling, scrap tire recycling, coal flying ash recycling, biomass utilization, and carbon capture by slag carbonization		Questionnaires, collaboration with national and local governmental agencies, institutes, and industrial persons; onsite survey. Research meetings and expert reviews; urban level hybrid physical input and monetary output model; hybrid evaluation model integrating process-based life cycle assessment and input-output analysis; calculation of increased or avoided consumption, and emission in the industrial symbiosis process and each related sector; trade-off emission; scenarios design	2017	[37]
China	Liuzhou		Iron and steel company, power plant, chemical company (ammonia production), hydrogen manufacturing, cement and construction material manufacturing companies, central heating for the residential sector, nearby plants and communities	Metallurgical gas, waste heat, waste plastics, scrap tires, and coal flying ash		Onsite survey, analytical approach integrating material flows analysis (includes material and energy flows analysis) and emergy evaluation model, avoided consumption and emissions for a company and CO_2 emission reduction, emergy evaluation index and dilution emergy	2017	[10]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	280 proper cities and 357 county-level cities		Electric power plant, cement plants, steel plants, district energy, residential and commercial buildings, food/beverage, and other low temperature industries	High-grade, medium-grade and low-grade waste heat, fly ash, and steel slag		What-If scenario modelling approach. Cross-sectoral symbiosis modelling though energy cascading and material exchange. Energy cascade algorithms. Material-exchange algorithms. Estimating reductions in fuel use, CO_2 and PM2.5 emissions at different scales, life-cycle analysis and national-economy-wide economic input output-based life-cycle analysis. PM2.5 Pollution and health benefit calculations and AERMOD atmospheric dispersion modeling system	2017	[102]
China	Wuhan		Pulp and paper industry, city greening, agriculture, paper downstream industries including printing, publishing and other corresponding industries, wastepaper collection and disposal industry, and wastewater disposal industry	Wastewater, sludge and waste paper		Integrated life cycle management assessment method on the resource flows of industrial ecosystem including the eco-environmental assessment by the life cycle assessment and the sustainable use assessment by an indicator system	2019	[103]
South Korea			Iron and steel industry: galvanized and aluminized steel sheets producer, electrolytic steel plates producer, and reinforced material producer for automobile tires	Wastewater		Mathematical optimization model. General algebraic modeling system software. Life cycle assessment and life cycle costing. Estimation of present value	2010	[104]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
South Korea			(i) magnesium plant and cement plant; (ii) magnesium plant and urban area	(i) waste slag; (ii) waste energy resources (waste wood, waste plastic and waste tire)		Interview with magnesium production-related specialists. Quantitative estimation of CO_2 emissions: CO_2 emissions from fuel combustion, CO_2 emissions from transportation, CO_2 emissions from electricity consumption and limestone calcination-related CO_2 credits. Uncertainty analysis	2015	[105]
South Korea	Ulsan		Industries, factories and companies and/or urban area (residential and non-residential buildings such as hypermarkets, department stores, office buildings and hospitals)	High and low-grade waste heat		Manager interviews. Scenarios analysis. Heat load analysis procedure (estimation of gross floor area of a building, calculation of heating and cooling area, connected heat load, and peak heat load, and estimation of heat demand quantity of the target region). CO_2 emission reductions from the avoided fuel in the company. Fuel cost reduction from the avoided fuel in the company	2018	[106]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Shinchi Town, Fukushima Prefecture		Coal-fired thermal power plants and plant factories	Waste heat		Technical and economic feasibility assessment, sensitivity analysis, cost-benefit assessment and spatial analysis. Energy generation model: influence on power generation efficiency, electricity loss for extracting heat energy, and required cost and additional CO_2 emissions to compensate for power generation losses. Energy distribution model: heat loss evaluation, pumping cost and CO_2 evaluation (energy consumption of the system, required cost, and additional CO_2 emissions in the operation of a pumping system), and pipeline installation cost (pipeline installation cost and annual rental cost with a discount rate method). Energy consumption model: estimated energy consumption due to heating in a plant factory	2014	[107]
Japan	Shinchi Town, Fukushima Prefecture		Natural gas power plant, coal-based thermal power plant, ceramic factory, chemical factory, urban area and greenhouse type plant factory	Waste heat		Model framework including energy system design, land use scenario, inventory survey and geographic analysis. District heating network design and simulation: hydraulic analysis, pipeline diameter, pressure drop, necessary pumping power and temperature drop. Cost-benefit assessment: economic costs (heat distribution cost, heat transport cost and management and maintenance cost), benefit of fuel cost reduction and CO_2 reduction. Sensitivity analysis	2018	[13]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Tanegashima		Combined heating and power plant, sugar mill, wood production industry, wood chip factory, wood pellet factory, and forestry industry	Waste heat, sugarcane bagasse, thinning residues, sawmill residues (sawdust and bark), and wood chipping residue (bark)		Interviews and discussions with the on-site experts and stakeholders. Scenario Analysis. Energy flow analysis. Greenhouse gas emissions based on life cycle analysis. Adjusted environmental load for a scenario	2016	[108]
Malaysia		4	Palm oil mill, palm oil-based biorefinery, and combined heat and power plant	Empty fruit bunches, palm mesocarp fiber, palm kernel shell, wet short fiber and dry short fiber		Disjunctive fuzzy optimization approach. Overall degree of satisfaction, annual gross profit, net present value, and payback period of a processing plant	2014	[109]
Malaysia			Various types of industries within the Halal Park		Cooperative safety management	Open-ended interview with seven industrial safety experts	2014	[110]
Malaysia	Kedah		Fertilizer industry, rubber block processor, tire producer, glove manufacturer, electricity co-generation, biomass disintegration, cement concrete industry, polymer asphalt binder industry, wastewater integrated facilities and methane recovery unit	Ammonia nitrogen waste, rubber waste, waste water from cooling system, rejected glove pieces, rubber traps, sludge and rubber woods, rubber latex waste and waste water	Co-generation unit for electricity, wastewater integration unit, methane development unit, and central storage unit	Questionnaires. SWOT analysis. Materials Flow Analysis and the Input-Output data based on previous Life Cycle Analysis data	2017	[111]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Turkey	Gaziantep		Manufacturing of textile products, food products, rubber and plastic products, leather products, chemicals and chemical products, other metallic and mineral products, ready-made clothing, furniture, fabricated metal products, paper and paper products, and wood and wood products, basic metal industry, production and distribution of electricity, gas, steam and aeration systems, and collection, disposal and recycling of wastes	Used carpets, PET wastes, animal hides, carpet and textile fibrous waste, waste polyurethane and ethylene-vinyl acetate, flax fiber residues, polyester and polyurethane based textile wastes, cotton and polypropylene fiber based textile wastes, dairy by-products, waste tyre rubber, granular and fibrous particles from a range of plastic, rubber and textile waste, wastewater treatment sludge, waste foundry sand, calcium carbonate wastes, polyvinyl chloride wastes, polyurethane foam wastes, waste polyvinyl alcohol, polypropylene-based plastic wastes, waste paint, waste glass, red mud, polypropylene-based carpet wastes, food processing wastes, dust, waste rubbers, black glass waste, acrylic butyl styrene, dried sludge, organic wastes (pistachio processing wastes, food processing wastes, etc.), synthetic shoe processing wastes, and waste heat		Industrial symbiosis match-making platform (ESOTA®, Industrial Symbiosis Opportunity Screening Tool). Assigning NACE and EWC codes to industries and wastes. Company and stakeholder visits, stakeholder analysis and workshops	2017	[112]
Turkey	Ankara	10	Machining, metals and metal processing, rubber, painting and plating sectors	Waste heat		Tool for defining data about companies and process, cleaner production potential and costs and environmental impact graph of processes. Analysis of mass balance and all materials for process work flows	2018	[113]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
India	Puducherry		Sugar, paper, galvanizing, granite, and gypsum industries, etc.			Survey method with open-ended questions. Analytical methods: trend analysis, causal chain analysis, policy analysis, training needs assessment, technology needs assessment and barrier analysis. Content analysis. SWOT analysis	2015	[114]
Bangladesh	Chittagong Export Processing Zone		Garments manufacturing company, textile mills, towel manufacturing company, shoe accessories company, power generation and distribution company, crown mills, incineration plant and purification plant	Waste heat, solid waste and wastewater		On-site energy audit and equipment/waste emission survey. Visits to companies. Input and output analysis. Feasibility analysis (techno-economics and environmental feasibilities assessment). Business model development	2015	[115]
Philippines	Laguna					Questionnaires and survey with ten participants from different sectors of the industrial park. Decision Making Trial and Evaluation Laboratory	2016	[116]
North America								
USA	Johnston, Chatham, Lee, Orange, Durham and Wake Counties, North Carolina	87	Pharmaceutical, computer, telecommunication equipment manufacturers, resin manufacturer, amino acids manufacturing, and tool manufacturing industries and municipal wastewater treatment plant	Acetone, carbon, desiccant, hydrochloric acid, methanol, packaging materials, plastic bags, sawdust, sodium hydroxide, wood ash, wood chips, wood fluff, absorbents, blasting media, coal ash, conveyor belts, copper, drums, electricity, ethanol, fiberglass, floppy disks, food waste, foundry sand, furniture fluff, glass vials, ink, paint, plastic, rubber blankets, steam, steel, sulfuric acid, unheated water, wire and wood		Telephone calls, in-plant interviews and site visits. Discussions with multiple potential suppliers and users and brainstorming sessions with local manufacturing experts. Geographic information system maps with an associated project database	2001	[60]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
USA	Texas		Recycling, remanufacturing and waste treatment firms	Commercial, industrial and municipal waste		Questionnaire survey of a sample of recycling, remanufacturing and waste treatment firms. Modified total design method	2005	[117]
USA	Pittsburgh		Roadway construction and/or repair, steel and iron industry	Coal ash, foundry sand, and slag		Geographic Information System data; highway density map, road density, and total highway density; optimization analysis; life cycle analysis (Pavement Life Cycle Assessment Tool for Environmental and Economic Effects program); transportation cost analysis	2008	[118]
Canada	Ontario		Solar photovoltaic manufacturing plant, glass manufacturing plant, glass recycling facility, greenhouses, and grow rooms	Crushed cullet, waste heat, and CO_2		Inputs and outputs analysis	2009	[119]
				South America				
Brazil			Agricultural activities, livestock sector, and alcohol-chemical industry	Industrial by-products, animal waste, straw, ashes, and bagasse		Economic evaluation; indexes of economic efficiency: financing, liquid present value, internal return tax, contribution margin, economical revenue, return time, equilibrium point, and accumulated cash register flow; environmental and social analysis; emergy method; emergy indices: transformity, emergy yield ratio, emergy investment ratio, environmental loading ratio, renewability, and emergy sustainability index	2007	[120]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Brazil	Norte Fluminense region	14	Sugarcane farm, sugar and ethanol production facilities, combined heat and power generation unit, biorefinery consisting of the Pre-treatment & Separation, Saccharification & Co-fermentation, and Concentration & Recovery units, soft drink production, distilled spirits production, animal feed production, industrial surfactants production, effluent treatment facility and biogas production unit, adhesives manufacturer, wax production, and lube oil re-refinery	Bagasse, straw, filter cake, vinasse, CO_2, fusel oil, used yeast, ash, lignin, pentose, mother liquor, flue gas and particulate matter, molasses, bio-SA off-specification, diluted salt effluent, off-gases (non-recycled portion), used lube oil, and other effluents		Interviews with stakeholders and coordinators and visit to the mill facilities; scenario analysis, mass balance, synergy matrix, and material flow analysis; environmental, social, and economic indicators: waste emission reduction, greenhouse gases savings, potential job creation, and feedstock remuneration premium from bio-SA production	2018	[121]
Colombia	Bogotá, Tocancipá, Sopó, Soacha, El Rosal, Cajicá, Madrid, Mosquera, Cota, Chía, Bojacá, San Francisco, Funza, Nemocón, Saboyá	34	Food processing (coffee), engineering, construction, waste management, beverage (soft drinks), chemical (specialty, agriculture polyethylene films), packaging, container, gas supply, food (dairy, bakery and snacks), glass, agriculture (flower, poultry, mushroom), construction supplies, Styrofoam, construction and home supplies, furniture, flower, consulting, cosmetic, wood, and restaurant	Wood from stowage, plastic waste, polystyrene foam, cardboard boxes, coffee residues, paper, cardboard, glass, sludge/fertilizer, fruit syrup, food residues, wood waste, mycelium, sawdust, plastic waste/geomembrane, Styrofoam, and drainage water	Service sharing: sludge management and shared collection of hazardous waste	Workshops with companies, observations, surveys to the representatives with questions that require evaluations and open answers and semi-structured interviews	2018	[34]
Africa								
Liberia	Konia		Piggery, rabbit farm, fishponds, rice mill, anaerobic digester, garden, and guest house	Rice bran, manure, and biogas digestate	Fishponds	Interviews with a Liberia nongovernmental organization staff; optimization model: maximum number of people supported per year	2014	[45]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Mauritius			Slaughterhouse, edible oil refinery, scrap metal recycling plant, cement manufacturer, wastewater treatment plant, construction products manufacturer, plants operating a boiler, biogas production plants, composting plant, animal feed manufacturer, and agro-industry	Scale, spent bleaching earth, sludge, slag, dust, and paunch manure		Desk analysis, interviews to recyclers, officers at the Ministry of Environment, Sustainable Development, Disaster, and Beach Management and environmental officers, and framework for adopting industrial symbiosis	2017	[122]
Egypt	Borg El-Arab		Food industry, textile factories, wood factory, metal factories, factories for paper products, construction materials factory, chemicals and pharmaceuticals factories, plastic factories, electrical and engineering products factories, brick production factory, animal feed production and fish farms, and organic fertilizers and soil amendments factories	Suspended solid particles, alkaline industrial drainage, chemicals packs and barrels, food residues (organic wastes), gypsum, metal scrub, paper sacks and chips, PVC residues, sawdust, plastic flashes, and wooden pallets		Data from internal unpublished sources at the Ministry of the Environment of Egypt	2018	[61]
				Oceania				
Australia	New South Wales		Serpentinite mining industry, carbonation plant, power generation plants, iron and steel making, and cement and concrete production	CO_2, waste ash, slag, tailings, and fly ash		Aspen modelling	2012	[123]
Australia	Kwinana	12	Titanium dioxide plant, fused materials company, refractory manufacturing industry, coal-fired plant, aluminum industry, chemical manufacturing, construction industry, water supply and treatment company, cement manufacturer, steel market mills, refinery, and fertilizers company	Petroleum coke, phosphate rock digestion off-gases, nitrogen oxides waste gases, and calcium chloride		Triple bottom-line perspective and preliminary sustainability assessment (social, economic, and environmental)	2013	[124]

[1] NE: Number of enterprises

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Economic, Environmental and Social Benefits of Adoption of Pyrolysis Process of Tires: A Feasible and Ecofriendly Mode to Reduce the Impacts of Scrap Tires in Brazil

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Abstract: This study addressed the development of a pilot plant for pyrolysis of scrap tires to obtain carbon black and other byproducts. The work was motivated by the goal of contributing to the development and dissemination of knowledge about existing technologies that allow modern economies to transform waste into valuable products, by documenting and discussing an empirical application in Brazil. Thispaper describes the development of a market for steel scrap, pyrolytic oil and carbon black products obtained from a vacuum pyrolysis process. The research work was conducted in Brazil, and was guided by the twofold purpose of reducing the environmental impacts, while gaining economical sustainability. Modern economies increasingly need to devise strategies to address energy generation while preserving natural ecosystems. These strategies include leveraging the use of renewable energy sources. Acknowledging that scrap tires hold an enormous potential as a sustainable energy option, this study aimed to contribute to the development and maturity of eco-friendly processing approaches to realize its full potential. The work involved a preliminary phase concerned with the operation of vacuum pyrolysis of scrap tires at a laboratorial scale, followed by the design of the pilot plant that operated for 10 years, at the time of the study, with a 100 kg/h batch flow. Results show that the yield of the pyrolysis process was 41% pyrolytic oil, 38% carbon black, 12% gas, and 8.9% steel scrap, with a calorific value of 36 MJ/kg per tire. The carbon black was composed of 90% carbon, and the pyrolytic oil was composed of 66% gasoline and 33% other oils, which have higher quality and can be commercialized with a potential profit over 3 million dollars/year.

Keywords: carbon credit; eco-efficiency; environmental cost accounting; pyrolysis; solid waste

1. Introduction

1.1. The Problem of Scrap Tires

The management of waste associated with end-of-life products is a public concern and a priority of policy debates. The end-of-life scrap tires represent an important issue notably for the implications they hold for public health and environment. Tires are made of non-biodegradable material, i.e. styrene-butadiene rubber (SBR), and for this reason there is a growing concern among developed economies about the need to prevent harmful environmental effects associated with tire waste. One option for improving the management of the scrap tires is processing end-of-life items for recovering its material. The recovery of scrap tires is done by rubber crumb (fine-grained or granulated tire rubber) and removal of fiber and steel elements, and by using the resulting outputs for new rubber products, such as playgrounds, sports surfacing, and rubber-modified asphalt. An alternative for addressing end-of-life waste tires is subjecting them to processes that yield outputs that are suitable for energy applications [1].

The amount of scrap tires is increasing significantly as result of rapid economic growth and development of the transport industry. According to statistics reported by Wang et al. [2] and Li et al. [3], approximately 3.0 billion tires are generated globally, with a predicted growth rate of at least 1.0 billion tires each year. North America, Europe, and Asia generate many scrap tires, accounting for almost 90% of global tire production [4,5]. The estimated growth for the worldwide tire demand is about 4.3% per year, and reached 2.9 billion units in 2017, while waste tire disposal in 2015 reached nearly 1 billion units [6–8]. In this scenario, recycling end-of-life tires becomes an urgent need because the accumulation of discarded tires holds serious environmental risks. While some end-of-life tires are recapped or ground for particular reuses, a great volume is simply dumped in rural areas or in landfills. When buried in landfills, they can eventually float to the surface. In piles, the non-biodegradable rubber can cause serious harm if ignited. Likewise, tires infested with mosquitoes are a subject of increasing concern [2,5].

Most countries do not yet have specific legislation concerning the collection of waste tires, and those that do are still researching how to increase their life cycle, as succeeded in Poland with the implementation of the urban solid waste law in 2012 [9]. In Brazil, an urban solid waste law was implemented in 2010 [10] andTurkey implemented the urban solid waste law in 2014 [11], Even in countries such as Spain, which implemented such laws in 2005, problems persist concerning the correct final destiny of the waste tires [12]. In contrast, countries such as USA, Germany, and Japan have been deploying this technology since the 1970s [13], e.g. New York has usedthe unserviceable tires for the generation of energy and production of gas, fuel oil, and carbon black since 1990 [14].

The European Union (EU) has prohibited the disposal of tires in landfills since 2009, and the recycling rate is 95% for the manufactured tires, at a cost of 1.78 Euros each. A share of 39% is recycled in retreading and 37% in energy cogeneration. Canada, Japan, and USA disclose that they recycle 89% of the tires produced by means of diversified processes, mainly in energy co-generation systems [5,15,16]. In the 2000s, Korea and Spain also adheredto pyrolysistechnologyforused tires [16,17].

According to Nourreddine [18], an EU draft directive states a goal that, by 2015, only 5% of a vehicle's weight can be disposed to discharge sites, and that a further 10% can be incinerated. Usually, the recycling of automotive vehicles is focused on recovering metals, while other materials in the form of shredder fluff are disposed to landfills. This material is currently incinerated for energy and carbon black production. The challenge remains because many countries donot have technology to meet the requirements specified in this directive.

The environmental problem caused by used tires is most noticeable in developing countries, as reported by Osahy et al. [4], who mentioned that 160,000 tons of waste tires are generated in South Africa annually, and up to 28 million used tires are dumped unlawfully or burned. Moreover, this figure is estimated to increase by 9.3 million yearly. The authors proposed the elimination of this waste through pyrolysis of used tires to obtain carbon black.

Banar et al. [19] reportedthat, in Turkey, while 8 million tires are produced per year, which is equivalent to 285,000 tons/year, the total installed capacity for recovering waste tires is 101 tons/year. In the same country, Aydin and Ilkiliç [6] were able to obtain a pyrolytic oil thatcan be used as fuel in diesel engines, after removal of excessive sulfur.

In 2012, more than 280 million tires were discarded in China, with a weight of 10.18 million tons. Scrap tires are insoluble and infusible, and are therefore difficult to degrade naturally. A lack of suitable techniques and economic factors over the years has led to scrap tires becoming a serious problem in terms of environmental pollution. At present, most scrap tires aredeposited in open or landfill sites, resulting in disposal problems and the increased risk of fires [3]. Various recycling methods have been developed over the years, such as retreading, incineration, and crumbling to produce rubber powder, but they all have significant limitations or drawbacks [3].

Developed countries have been consistently advised to prevent harmful effects to the environment. One of the options for the management of the scrap tires is material recovery. A prevalent alternative to recover scrap tires is rubber crumb, together with the removal of embedded fiberfor the purpose of new products such asplaygrounds and surfacing solutions [13,20–22]. However, according to Banar et al. [19], Williams [22], and Martínz et al. [23], pyrolysis must be regarded asa viable and relevant alternative to recycle the tires because its various derivatives have a greater scope for application and valorization.

1.2. Pyrolysis as an Ecofriendly Solution to the Scrap Tires

Pyrolysis of scrap tires has evolved as a viable alternative to overcome the practices of incorrect disposal of tire waste. Pyrolysis processes can produce tire derived oils that may be used as fuel or added to conventional fuels, producing fuel blends with improved properties at a reduced cost. Pyrolysis is a process that can contribute to overcome the practices of disposal of tire residues from inadequate sites, therefore standing out as a sustainable process to produce alternative fuels [15].

Roy et al. [5] defined the vacuum pyrolysis as the combustion of organic substances in the absence of air. It enables the production of large quantities of pyrolysis oils from organic substances. Vacuum minimizes secondary reactions such as thermal cracking, repolymerization and recondensation reactions, gas phase collision, catalytic cracking and redox reactions. If the vapor phase products are quenched, the yield of organic liquids such as pyrolysis oils is increased at the expense of solid residues and gases. The physicochemical properties of the end-products are a function of the pyrolytic temperature [24]. According to Al-Lal et al. [25], Martinez et al. [23] and Raclavská et al. [26], the pyrolysis processcanbe used to obtain fuel from biomass, coal, lube oil, plastic and tire wastes.

In the last three decades, many products have been derived, thus affirming the interest of pyrolysis for waste tires. For example, Yousefi et al. [27] developed polymer-modified asphalts prepared by incorporating recycled polyethylene and a used-tire-derived pyrolytic oil residue in asphalt. Its characteristics showed superior properties for the modified asphalts at high temperatures.

At low temperatures, the bitumen becomes brittle and cracks, while, at high temperatures, it softens with the result that the bitumen binder either migrates to the surface or the pavement tends to be put under stress. To solve these problems, Chaala et al. [28] mixed carbon black with bitumen at levels between 5% and 30%, reaching significant results on the rheological behavior of asphalt obtained.

Canada ranks among the first countries touse tires as a source of energy and of valuable chemical products by thermal decomposition of rubber in a pilot plant. Yields are 55% oil, 25% carbon black, 9% steel, 5% fiber and 6% gas. The maximum recovery of oil isperformed at 415 °C below 2 kPa. The energy obtained from tire pyrolysis has been estimated in 700 kJ/kg, with a mass flow of 200 kg/h [29].

However, according to Roy et al. [5], the pyrolysis of scrap tires has been, thusfar, uneconomical due to the absence of an established market for oil and, in particular, for the pyrolytic carbon black product. Therefore, most existing research ontire pyrolysis is more concerned with obtaining pyrolytic oil, which can be used in diesel engines. Several authors showed that the application of pyrolytic oil in engines is feasible, because it hasa quality equivalent to diesel oil [4,6,30–36]. Mui et al. [33] also showed that it is possible to use carbon black in the treatment of textile industries effluents. Debek and Walendziewski [35] showed that, after hydrorefining oil from tire pyrolysis, it is possible to obtain good quality fuels that can be used in passenger carsand vans.

Furthermore, in a survey addressing environmental impacts, Huijbregts et al. [36] calculated product-specific ecological footprints from consistent and quality-controlled life cycle information of 2630 products and services, including energy, materials, transport, waste treatment and infrastructural processes. They showed that the disposition of tires to a waste incineration process has an ecological footprint of 72 m^2/year, while its disposal in the landfills hasan ecological footprint equal to 113 m^2/year, that is, its impact is reduced by almost 40% when incinerated. In this way, it is evident that the incineration of tires is a greener way than disposal in dumps or landfills.

Currently, this technique ranks among the best to mitigate the contamination from tires discarded inadequately and consequently it concedes a better end-life to the tires [25,28–41].

According to Umeki et al. [24], the pyrolysis oil of the scrap tires has black coloration, strong odor and specific gravity around 0.93 g/cm^3. In addition, the compositional analysis of tire pyrolytic oil (TPO) describes the liquid as a complex mixture, composed mainly of aromatic compounds and olefins, containing important fuels such as gasoline and diesels. They concluded that the fuel blend's properties point to a potential viability of using the TPO in mixture with diesel. This would be an alternative fuel for automotive and industrial uses and for the replacement of conventional petroleum fuels.

The energy efficiency of the diesel oil blend with the tire pyrolysis oil was tested on a 440 cm^3 single-cylinder diesel engine. Engine performance, evaluated at different engine speed and loads, showed that the use of 20% of weight (%wt) blend does not cause significant differences in terms of torque, power, specific fuel consumption, and exhaust emissions, compared to those obtained using diesel fuel [40]. Similar results were obtained by Wang et al. [2] whotested several diesel oil blends with pyrolysis oil from waste tires on a diesel engine for rotations up to 2500 rpm.

In Iran, Hossain et al. [41] produced a pyrolysis oil from a mixture of scrap tire and rice husk with characteristics very close to petroleum oil. The highest fuel oil yield was 52 wt% when a mixture of 50 wt% tire and 50% rice husks was used, which was pyrolyzed at 450 °C. The results show that it is possible to obtain liquid products comparable to petroleum fuels, and valuable chemical feedstock from the selected wastes if the pyrolysis conditions are chosen according to the products to be obtained.

Ayanoglu and Yumrutas [11] producedgasoline- and diesel-like fuels from waste tire oil by using catalytic pyrolysis in a heat reactor. After the distillation processes, the fractions obtained were composed of 18 wt% of light oil (gasoline), 70 wt% of heavy oil (diesel fuel) and 12 wt% of residues. Furthermore, the carbon distribution of GLF (C_4-C_{12}) and DLF (C_{13}-C_{17}) samples was close to the one of standard fuels.

Li et al. [3] developed a continuous process of pyrolysis from the scrap in the presence and absence of catalysts. The maximum yield of derived oil was up to 55.65 wt% at the optimum temperature of 500 °C. The catalytic pyrolysis was performed using 1.0 wt% (on a scrap tire weight basis) of catalysts. They concluded that the derived oil can therefore be used as a petrochemical feedstock for producing high-value-added chemical products or as fuel oil.

Ahoor and Zandi-Atashbar [1] obtained pyrolysis oil under an argon atmosphere at 407.3 °C. They achieved 12 wt% of fuel oil, the highest yield. Several works have shown that the derived oil contains variable concentrations of valuable aromatic and aliphatic compounds such as butadiene, D-limonene, benzene, toluene, and xylenes, which could be used directly as substitutes for conventional fuels or petrochemical feedstocks as a potential source of light aromatics [3,42].

These tire pyrolysis plants are not yet widespread in underdeveloped countries because of their high cost of deployment. However, researchers have dedicated efforts to enable its implementation as follows.

In Turkey, Ayanoglu and Yumrutas [11] developed a low-cost tire pyrolysis plant. The main part of pyrolysis unit cost was US$11,477. The main part can be used for 10 years with a full load production. Amortization of the pyrolysis unit was 0.157 US$/L, and they realized that the cost of production of the other derivatives was above the price paid for oil products in Turkey.

To minimize the cost of production, Luo and Feng [43] used the waste heat of blast-furnace slag in the production of fuel oil and combustible gas by catalytic pyrolysis, as a novel waste energy recycling strategy. Their results show that there was an upgrade in the quality of pyrolysis oil.

1.3. Brazilian Situation Regarding the Management of Scrap Tires

According to the National Association of Tire Manufacturers (ANIP), Brazil has 20 companies that manufacture tires, which are responsible for 150,000 jobs [44]. In 2014, the production reached 68.8 million tires. There was a 26% increase in tire production compared to 2006 and, due to imports, 74.9 million tires were sold that same year [44].

According to Machin et al. [10], the production of tires in 2014 by the Brazilian industry totaled 70.8 million units, which was a small reduction compared to 2013, when the sector achieved a historical record. According to the sectorial balance presented by ANIP, Brazil closed 2016 with a fall of 1.1% in total tire production as compared to 2015 [44]. From 2014 to 2015, the accounts also closed in the red, with a decrease of 1.2%. The ANIP balance sheet presented at the end of December 2017 showed a growth of 2.4% in tire sales, as compared to the same period in 2016, which suggests a slight recovery of the sector, following two years of crisis [44].

The Normative Instruction N°001/2010, from the National Council of the Environmental of Brazil (CONAMA), regulates the procedure that manufacturers and importers must meet for registration, calculation of goals and confirmation of the allocation. This law states that 100% of the outstanding tires in the country should be recycled, and determines that the companies are responsible for handling the end of life-cycle and end destination of tires [45].

Manufacturers and tire importers must prepare a management plan to collect, store, and dispose scrap tires within six months after the publication of Resolution No.416/09. The Resolution specifies that, in cities with over 100,000 habitants, at least onecollection point should be installed, within oneyear following the publication of the resolution. The new resolution does not consider the reform of tires as recycling, but as an activity that prolongs tire life [45].

However, in São Paulo, for instance, only fourcollection pointswhere created when the regulation proposed the creation of 120. In addition, there is no report about the volume of discarded tires in landfills [16]. Currently, there is no register about the collection points in other cities from Brazil. This demonstrates a disregard of companies towards Brazilian politics, that probably can be explained by the fact that companies want to avoid the costs associated with the collection and implementation of ecologically friendly processes for the end destination of the tires [5].

According to ANIP in 2016, the goal established by CONAMA was reached and the manufacturers of tires were able to give a correct destination to 404,328.13 tons of waste tires and, from January to September 2017, over 360,000 tons of tires had the correct destination, which corresponds to more than 4.0 million tons of waste tires collected since 2009 [44]. However, according to Lagaritos and Tenório [16], Brazil only repairs half of the waste tires at a cost of US$0.45/tire, which can be proven by the tires in dumps, rivers and lakes that are constantly caught by public inspection entities.

However, according to Roy et al. [29], all of the tire recycling and treatment processes cited above have some disadvantages. Retreading can only be performed when the carcass is not damaged. When tires are used as solid fuel, polycyclic aromatic hydrocarbons and soot are produced. Therefore, expensive gas cleaning devices are necessary for the removal of potentially hazardous compounds. Tire grinding is very expensive since it is performed at cryogenic temperatures or requires energy-intensive mechanical equipment.

A tire recycling technique, used in many countries, but not yet extensively used in Brazil, is the tire pyrolysis. The outputs of this processing alternative can be used in the preparation of dyes for paints and varnishes, as blends for rubber or asphalt and obtaining some chemicals such as limonene and fuel additives [27,28,46,47].

As noted, tire pyrolysis is a feasible and ecologically friendly alternative as the end destination of tires [38], since it produces energy and various chemical products used as fuels (including gasoline), dyes, polymers, asphalts, etc.

This paper describes a case study in Brazil, which illustrates how to reduce the environmental impacts caused by tire disposal in a sanitary landfill alongside making the process profitable, by vacuum pyrolysis. Moreover, this work aspires to contribute to the development of a market for the pyrolytic oil and carbon black products obtained from a vacuum pyrolysis process, in Brazil. Following a preliminary process of vacuum pyrolysis of used tires conducted in laboratory, the process has been scaled up over the last 10 years from a batch to pilot plant with 100 kg/h capacity.

2. Materials and Methods

2.1. Layout of Tire Pyrolysis Plant

Figure 1 shows a scheme of the tire pyrolysis tire where this work was developed. The recycling cycle was composed by a sector tire reception, followed by a sector for storage while pre-heating them at 100–110 °C. All processing conditions were based on Chaala et al. [28] and Roy et al. [5]. The heat was generated by a furnace that fires fuel oils. Tire samples were loaded by a conveyor wagon that entered them into the reactor for putting the samples in contact with internal heat. The reactor has a capacity of heating two wagon at the same time. Gaseous products from the reactor were condensed in a distillation tower for separation of gas, light oil, heavy oil, and crude oil, whichare used as fuel, polymers and asphalt components. The solid products from reactor were cooled in a heat exchanger, after which a magnetic separation to remove metalwas applied. Afterwards, they were crushed in a blade mill and mashed to obtain carbon black, which is sold to dyeing companies. However, to obtain the experimental data, a scale up of the reactor was fed with a mass flow of 25 kg/h of tires at 600 ± 50 °C and 20 kPa. The reactor temperature was monitored on line by an internal thermostat. Samples were collected periodically for monitoring the pyrolysis of tires.

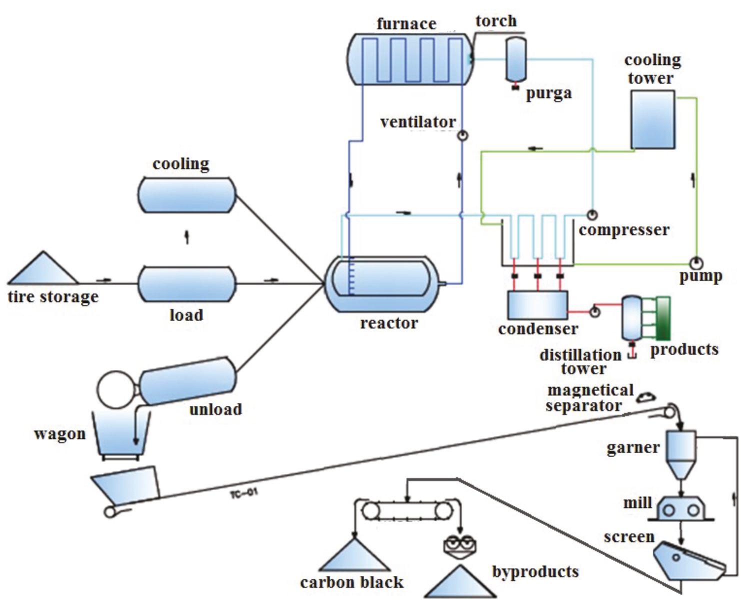

Figure 1. The used tire pyrocycling process flow sheet.

2.2. Chemical Analysis of Products

Characterization of liquid product: The chemical composition was analyzed by gas chromatography coupled with mass spectroscopy (GC-MS), near region (NMR) and Fourier transform infrared spectroscopy (FT-IR) and standard methods of the American Society for Testing and Materials (ASTM). The inferior calorific value was measured by the ASTM D129 method. The flash points of oils were determined by the Dean and Stark method. The value of carbon Conradson residue was obtained by ASTM D524. The ketone index, the sulfur content and density were measuredby the ASTM D4737, ASTM D3177 and ASTM D4052 methods, respectively [48]. The elementary composition was determined with a LECO CHN-600 apparatus [30,34,35,38,49].

Characterization of Carbon black: This product wascharacterized by nitrogen adsorption, electron spectroscopy for chemical analysis (ESCA) and inverse chromatography [49].

A shelf life study of pyrolytic oil was done to assess the possibility of using oil as a fuel additive. To this end, pyrolytic oil was mixed at 2% and 3% with diesel oil and samples were storedfor 21 days in dark conditions. Afterwards, all ANP parameters were measured in samples [48] asrequired by Brazilian laws.

2.3. Price Description and Cost Analysis

Former records registered the investments in plant construction aroundUS$ 1.25 million, for an estimated 10-year lifetime. The cost for plant maintenance (depreciation) was 4% of the total investment, thusthe annual fixed costs totaledUS$130,000. The warehouse rate is a revenue source and thusUS$0.45/tire will be charged tothe tire companies, in accordance with Lagarinos and Tenório [16], a price already practiced in Brazilian market. According to MFRural [50], carbon black is sold in Brazil at US$1.50/kg and the fuel additive is sold in Brazil at 3.50 US$/L. According to SEFAZ [51], steel scrap is sold for0.03 US$/kg and, according to SINDGAS [52], the sale price of the cylinder containing 13 kg GLP gas was US$19.36 inSeptember 2017, in Brazil. The average costof energy in the region of the company is 0.13 US$/kWh [53]. The calculation was based on maximum capacity of pyrolytic reactor of 876 ton/year (100 kg/h), considering its operation in continuous flow feeding by skip cars. This way, the calculations was based on annual mass processed by the company. All costs and profits are summarized in Tables 6–8. All calculation procedures were presented by Ayanoglu and Yumrutas [1]; Almeida et al. [54]; Benvenga et al., [55]; Giraçol et al. [56] and Passarini et al. [57].

3. Results and Discussion

3.1. Performance of the Pyrolysis Process

Figure 2 shows the variations of temperatures for the combustion gas (outside), of the inner wall of the reactor and the reaction temperatures of the materials measured during the pyrolysis process. Temperature stabilization occurredafter 40 min of process time due to heat transfer between the environments involved until the thermal equilibrium of the reacting systemwas reached. This time can be considered as the beginning of the standing state of tire pyrolysis process. Finally, there was a drop in temperature due to disrupting the power supply of the system, as this is a batch process. A summary of the thermal analysis is shown in Table 1.

In this continuous process, the reaction heat isused forpreheating the next sample of tire, which are loaded into the reactor by conveyor wagons and the initial 40 minof the process timeis eliminated, thus reducing the overall production time [2,29].

To determine the proportion of the liquid formed, and the solid and gaseous products, the masses of each component were measured. Table 1 shows the mass balance obtained with three assays for the pyrolysis of crushed tire samples. As noted, the time for the complete reaction was 1.43 h and the major components of pyrolysis productswere 41% of pyrolysis oil and 38% carbon black.

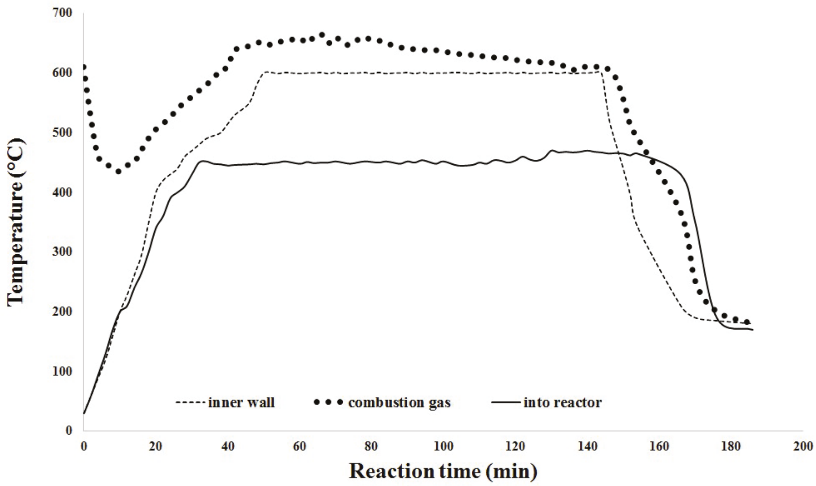

Figure 2. Variation of temperatures during the tire pyrolysis process.

Table 1. Mass balance of tire pyrolysis process at 600 °C and 20 kPa.

Sample	Carbon Black (%)	Pyrolytic Oil (%)	Pyrolytic Gas (%)	Stell Scrap (%)	Reaction Time (h)
Tires	38.35± 0.25	40.72± 4.16	12.12 ± 4.32	8.95± 0.05	1.43
	Calorific value (kJ/kg)			34,842 ± 4,174	

Table 2 shows the chemical composition of the gaseous fraction samples that passed in the distillation column. As noted, the major component of the gaseous fraction are fuel gases composed of48.85% natural gas (methane and ethane), 26.45% gas liquefied under pressure (GLP) (propane and butane), and 24.70% CO_2 derived from tire combustion. The liquid fraction obtained in this work was light oil of 0.95 specific gravity and dark color, composed of66% gasoline, 10% hexanes that can be used as an additive to gasoline (limonene) [6,29,48] and 24% high oils that can be used as fuel for blast ovens [48].

Tables 1 and 2 show the analysis of lower calorific power and gases obtained from tire pyrolysis. The calorific values in this study were: 36 MJ/kg for tire, 42 MJ/kg for GLP and 60 MJ/kg for natural gas. These values can be regarded as good since it is a mixture of natural gas and GLP (methane, ethane, propane and butane). These products can be used as an energy source for heat generation and, therefore, can be negotiated by the company as further products generated in the process.

In a similar research work, Roy et al. [29] obtained yields around 55% oil, 25% carbon black, 9% steel, 5% fiber and 6% gas. The specific gravity of this oil was 0.95, its gross heating value was 43 MJ/kg and total sulfur content about 0.8%. It was rich in benzol and other petrochemical components. This oil is suitable for mixing with asphalt [27,28].

The yield of the oil was higher than those obtained by Ahoor and Zandi-Atashbar [1] and Ayanoglu and Yumrutas [11], but smaller than those obtained by Li et al. [3] and Hossain et al. [40].

However, according to Alkhatib et al. [40], the oil composition depends on the heat received by the scrap tire, and in the best condition they obtained 45% oil. It was observed that increasing the heating power supplied to the pyrolysis reactor from 750 to 1500W resulted in an 11% increase of oil produced; however, the tar was too high.

Table 2. Results of chromatographic analysis gaseous fraction from tire pyrolysis to show its chemical composition.

Substances	Mass Composition (g/g, %)
Carbondioxide (CO_2)	24.70 ± 0.23
Metane (CH_4)	36.77 ± 4.15
Etane (C_2H_6)	12.09 ± 1.38
Propane (C_3H_8)	9.19 ± 2.05
Isobutane (C_4H_{10})	1.94 ± 0.20
2-Metilpropane (C_4H_{10})	6.57 ± 0.67
2-Metilpropene (C_4H_{10})	6.30 ± 1.38
n-Butane (C_4H_{10})	2.44 ± 0.20
Natural gas calorific value (kJ/kg)	42,420 ±3089
GLP calorific value (kJ/kg)	60,128 ±1256

Novicki and Martignoni [58] statedtheir tire calorific value was 30.2 MJ/kg, while the calorific value of their gas was 33.6 MJ/kg. Thus, the tire pyrolysis and GLP calorific values obtained in this work were higher than those ofNovicki and Martignoni [58].

However, other authors achieved higher values for energy generated by tire pyrolysis, e.g. Banar et al. [19] obtained a calorific value of 37.5 MJ/kg and Oliveira et al. [59] measured the calorific value at 42.0 MJ/kg.

3.2. Pyrolytic Oil as an Additive to Fuel

Table 3 shows the chemical composition of samples of the liquid fraction retained in the distillation column by gas chromatography. The liquid fraction obtained in this work was light oil of 0.95 specific gravity and dark color, which was composed of 66% gasoline, 10% hexanes that can be used as an additive to gasoline (limonene) [28,47] and 24% high oils that can be used as fuel for blast ovens [31].

As noted, the average molecular weight of the blend of oils is low, indicating it as an additive for other fuels. According to Santos et al. [60,61], even if the oil has a high molecular weight, it would be an optimal fuel in blast furnaces or cogeneration as shown by Banar et al. [19] and Santos et al. [60,61].

According to Santos et al. [60,61], oil companies have expressed interest in unconventional oil as alternative resources for energy supply, mainly because an increase of 40% in world market energy consumption is forecasted for 2035, and this would facilitate the selling of oil produced from pyrolysis of used tires.

Garcías-Contreras et al. [62] developed a residential boiler of 29.1 kW using a tire pyrolysis liquid (TPL)/diesel fuel blend (50/50 vol.%), as an alternative to heat in households. When they compared the exhaust temperature of diesel combustion gases with the TPL blend, there were no differences and both fuels tested increased the water temperature similarly. This demonstrates the feasibility of using tire pyrolysis oil in boiler. Wang et al. [2] and Martinez et al. [23] also observed the similarities of tire pyrolysis oil andpetroleum. However, Frigo et al. [40] noted that in vitro assays on particulate emission for diesel and TPL/diesel blend had similar cytotoxic potency and no genotoxic effect.

Table 4 shows the results of fluid analyses of quality of diesel oil mixed to pyrolytic oil, ascompared with the ANP standards [48].

The liquid obtained by condensation of the reaction vapors showed a dark aspect, probably due to the presence of fine particulate matter in suspension (carbon). To test the liquid fraction as an additive in fuel, it was mixed at 2% or 3% with diesel oil. Table 4 shows the analysis of diesel oil additive after 21 days of storage. For a better understanding of the values, Table 4 also includes the limits required by National Agency of Petroleum [48] of Brazil for distillation temperature and the products obtained from petroleum decomposition process.

Table 3. Of chromatographic analysis of liquid fraction (oil) from tire pyrolysis to show its chemical composition.

Substances	Mass Percent (g/g, %)
Isopentane (C_5H_{12})	1.78 ± 0.08
1-Pentene (C_5H_{10})	1.07 ± 0.08
2-Pentene (C_5H_{10})	7.00 ± 0.12
1,3-Pentadiene (C_5H_8)	36.47 ± 0.67
2-Metil-1butene (C_5H_{10})	0.32 ± 0.08
2-Metil-2butene (C_5H_{10})	17.84 ± 0.67
n-Pentane (C_5H_{12})	1.38 ± 0.08
Hexanes(~C6)	10.09 ± 4.15
Higher oils	24.05 ± 0.67

This analysis aimed to determine the shelf life of the diesel oils by simulating storage conditions of the fuel and checking the formation of turbidity and precipitation of materials in the liquid. This test showed that all samples studiedat2% mix remained within this parameter. All 3% samples showed deposition material and some turbidity, thus did not meet ANP specifications [48].

Table 4. Shelf life study of thediesel oiladditive.

Characteristic	Control	Pyrolyticoil		ANP Standard
	Dieseloil	2%	3%	
Aspect	Clear	Clear	Clear	Clear
Cor	2	2	Black	3
Boil point (°C)	132	132	131	Note
Temperature (50% evaporate)	274	274	288	245 to 310
Temperature (85%evaporate)	340	340	346	370
Evaporation point (°C)	382	382	392	Note
Specificmass (Kg/m^3)	854	854	874	220 to 880
ketone index	0	0	0	45
Sulfur (mg/Kg)	400	400	1150	1800
Flash point (°C)	51	51	57	38

Trying to encourage the recycling of tires, Banar et al. [19] obtained a pyrolytic oil of high molecular weight from pyrolysis of used tires in Turkey, which canbe used for energy cogeneration according to the country laws. The oil obtained by Chaala et al. [28] had a specific gravity of 0.95, gross heating value of43 M J/kg and total sulfur content of about 0.8%. It was rich in benzol and other petrochemical components, i.e. it was also a heavy oil. However, in this work, pyrolytic oil was mixed with fuel oil to show it can used as fuel for furnaces, but it also can be used as motor fuel, according to Brazilian laws [47].

Ahoor and Zandi-Atashbar [1], Ayanoglu and Yumrutas [11], Hossain et al. [41], and Umeki et al. [24] obtained an oil of similar quality to that presented in this work, reporting that the oil had properties similar to a gasoline or a petroleum oil. Frigo et al. [43] and Wang et al. [2] demonstrated the energy efficiency of this oil in the production of energy in a diesel engine. Moreover, this viability of pyrolytic oil used in engines wasalready confirmed by other authors [4,6,30–36,38,58].

3.3. Characterization of the Solid Fraction

The solid fraction, which is inside the reactor after the pyrolysis process, is scrap metal and/or coal. The coal, depending on the reaction temperature, can be milled and sold as semi-reinforcing filler or filler for the rubber and paint industries, and sold as dyes or coal for use as fuel. In the case of metals contained in tires, they may be sold as scrap tometallurgic companies. To determine the proportion of carbon, nitrogen, hydrogen and sulfur, elemental composition measurements were performed aiming at possible application of these materials in the steel industry as a source of "fine" for blast furnace base injection. Thus, the parameters Fixed Carbon (FC), volatile and ash were determined. These variables are chemical parameters of reference for the quality of coal fines for steel.

Table 5 shows thethermogravimetricanalysis results for solid fraction in an oxygen atmosphere. In this analysis, the carbon was oxidized at 400–600 °C, whereby the organic material was transformed into pure carbon. The carbon black was 3% volatiles, 9% ashes, and 88% fixed carbon, of which 86% was pure carbon. According to Roy et al. [29], this composition ensures its use as raw material for dyeing and inks industries, in addition to other applications cited throughout the text. Sulfur is not a desirable component in carbon black, and the sulfur content (2%) obtained in this study was consistent with most research work reported [5,19,28].

Osayi et al. [4] conducted a review and found ranges of 74–86% for C, 5.8–7.5% for H, 0.2–1.8% for N, 1.0–2.1% for S and 2.1–14% for ashes. However, Banar et al. [19] cited a composition with 82.5% carbon, 6.9% hydrogen, 8.4% oxygen, 1.7 sulfur and 0.5% nitrogen, for the carbon black obtained in their work. Therefore, the carbon content of the product obtained in this study was better than those cited by Banar et al. [19] and Osayi et al. [4].

Novicki and Martignoni [58] stated that a carbon black ideal to steel industry must have more than 75% carbon content and less than 10% volatile content. Moreover, Banar et al. [19] obtained carbon black with 24.1% fixed carbon, 65.5% volatiles, 9.63% ashes and 0.84% moisture from tire pyrolysis. Chaala et al. [28] broughta carbon blackto theCanadian market with 77% pure carbon,19% ash and 4%volatiles. As can be seen, thecarbon black obtained in this study hasa better quality than that of Banar et al. [19] as well asthose required by the Brazilian steel industries and Canadian market.

Table 5. Evaluation of carbon black obtained in this work.

Source	Percent composition (%)			Elemental composition (%)				
	Volatile	Ash	FC	C	H	N	S	Other
Carbon Black	3.25	9.05	87.7	86.49	1.30	0.51	1.96	9.74
Deviation	0.55	2.05	2.60	2.70	0.01	0.18	0.13	2.38

OBS: FC, fixed carbon.

3.4. Environmental Cost Accounting of Pyrolysis Process of Tires

Tables 6–8 show the profitability of 876 ton/year (100 kg/h) plant for vacuum pyrolysis of used tires. Because the pyrolysis process aims to be auto-sufficient in energy, the fuel oil used in the startup process was not considered in this calculation, because its costs couldbe addressed as relatively insignificant as they need only one utilization over the whole operation period.

Table 6. Calculation of expenses of process.

Type of Expenditure	Quantity	Annual Cost (US$/year)
Financial expense		124800.00
Taxes on sale (%)	18	346,923.39
Depreciation (%)	4	5000.00
Cost employees		
Engineer	1	18000.00
Technicians	9	75600.00
Administrative offices	2	8400.00
Taxes on salaries (%)	36	36720.00
Sum cost employees		**138,720.00**
Total expenses (US$/year)		**615,443.39**

As shown in Table 6, the higher process costs were associated with the commercial taxes (55%) due to product sale, salaries (23%) and the financing of the plant (21%). Even in this scenario, the costs amounted to one third of the revenues.

Table 7 displays the revenue sources for process the tire pyrolysis. It shows that the main products influencing the revenues (87.6%) were the pyrolytic oil and the carbon black, at 61.5% and 26.1%, respectively, reaching a total revenue of US$ 1.927 million and a total profit US$ 1.312 million. It is also noticeable that tire companies need to pay rights concerning the tire disposals, according to the Brazilian law, thusthe pyrolytic plant has an additional revenue of more than US$78,000 per year for tire storage [16].

For a pyrolytic plant of 200 kg/h of tire, Roy et al. [29] demonstrated that the process feasibility is promising, with returns on investment of 31% after three years of operation, in Canada. Based on this and the data inTable 6, all the company's financing costs can be covered by the total profit of the first year of operation alone. In this way, the plan proposed by this work proved to be three times more economically viable than the one described by Roy et al. [29].

Table 7. Calculation of the revenues of the tire pyrolysis.

Product	Quantity		Price (US$/Unit)	Individual Revenue (US$/year)
	Hourly (kg/h)	Annual (kg/year)		
Pyrolytic Oil (m^3)	40.68	338,539	3500.00	1.184,886.40
Carbon Black (ton)	38.31	335,596	1500.00	50,3393.40
Steel scrap (ton)	8.9	77,964	30.00	2,338.92
GLP (13 kg)	12.1	8,154	19.36	157,893.44
Tire storage (unit)	20	175,200	0.45	78,840.00
Revenues (US$/year)			**1,927,325.16**	
Total Profit (US$/year)			**1,311,908.77**	

Table 8 shows other possible gains with unusual by products such as carbon credit and energy sale from cogeneration. As can be seen, more than 1600 carbon credits can be claimed after certification by governmental certifying agency and in addition to the US$15,500 the company gains an image of ecofriendly company, which favors the marketing of its products. In addition, it is possible to sell the energy generated during the tire pyrolysis to an energy company, as is the practice in the context of the Brazilian alcohol industry, leading to an additional gain of US$2.445 million per year. Adding these values and subtracting commercial taxes due to product sales, leads to a total profit due to unusual byproducts of US$2.017 million per year.

Table 8. With unusual by products per year.

By emissions	Quantity	Carbon credit (ton CO_2)		Price (US$)	Partial profit (US$)
Tire (ton)	876	1,016.16		9.25	9,399.48
Energy (GW)	26.865	658.20		9.25	6,088.35
Sum		1,674.36		-	15,487.83
By cogeneration	Quantity	Conversion Efficiency (%)	Price (US$/kW)	Expenses (US$)	Partial profit (US$)
Energy (GW)	26.865	70	0.13		2,444,730.00
Taxes on sale (%)	18			442,839.30	
Profit of unusual byproducts (US$/year)					**2,017,379.00**
Total profit + unusual profit (US$/year)					**3,329,287.77**

Overall it is possible to reach a total profit of US$3.329 million per year. If the company wishes to pay completely the funding, its profit would be US$2.204 million in the first year and US$3.454 million in the following years. This project is more economically viable than projects described by Ayanoglu and Yumrutas [11] and Roy et al. [5].

3.5. Advantages of Tire Pyrolysis

Tire pyrolysis is energetically self-sufficienct, given that the energy required for pyrolysis comes from the process itself [38,63,64]. The process promotes tire recycling, namely the rubbersand metals contained in these materials. Moreover, it is a clean production process, because there is no usable waste recycling so it does not generate environmental liabilities [36,64].

The process has commercial viability since the sub-products generated have a production cost lower than the market prices [11,36,63,64]. Other advantages include the fact that the process is easy to operate and maintain, with low costs [11]; it does not generate odors [16,64]; and it is an innovative and environmentally friendly solution for old tires [63,64].

There will be revenue upon receipt of tires or rubber products, thusthere is no cost for raw materials, because the Brazilian company manufacturing and marketing tires are required to give an environmentally friendly end tires; thus, it can charge fees for receiving the tires from these companies [16,43].

An additional benefit is the possibility of generating carbon credits [55–57] and increase local employmentas well as financial transactions [36,63,64], adding to the social sustainability arguments.

The pyrolysis process can eliminate problems related to several issues, including the needs for space for tire storage, anddifficulties in compression, in transport, and in handling. Tires buried in soil or sunkin water tend to rise to the surface, and stacked tires serve as an ecosystem to rodents and insects that are disease transmission agents such as dengue, zika virusand yellow fever. When burnt, tires release a highly toxic waste in thesoil and increaseair pollution. Moreover, a buriedtire hasno foreseeable deadline forits decomposition.

This process is so innovative that there will be no environmental liabilities, fitting in clean production strategies [36].

Moreover, it will produce various raw materials that are used in tires, rubber products, chemical, smelting, recycling and petrol industries, as well as in thermal boilers [5,16,17,38,41].

According to Li et al. [3], pyrolysis as a viable recycling process that has potential advantages in terms of energy recovery and mitigating the disposal problem. The products of pyrolytic degradation of scrap tires could be reused as high-calorific-value gas to meet the energy requirements of processing plants, oil for boiler fuel, or high-value-added chemical feedstocks and the char formed could be used as low-grade activated carbon or carbon black. It has been proved that the derived oil is more suitable for making high-value-added chemicals than for use as fuel, because it contains large amounts of single-ring aromatics [36].

3.6. Strategies to Acquire Raw Materials and the Sale of By-Products

Several alternatives can be advanced for the acquisition of raw materials and the sale of byproducts. Raw materialscan be channeled via large distribution networks that includemunicipalities, ANIP, eco-points and companies of retreads or tire sales. As for byproducts, their sale could be supported by marketing strategies aimed at the valorization of the products that result from the recycling process, via severalresellers and distributors, according to the characteristics of the different types of by-products as follows. The metal components are suitable for selling as scrap for industry and steel production [5,16,17]. Carbon black can be used as a load for semi-reinforcing rubber products and dye industry [5,16,17]. Coal can be usedas a raw material or as an energy source for steel companies [5,16,17]. Benzene has applications in chemical industries and laboratories. It is commonly used as an organic solvent andas a raw material for the production of many organic compounds [39,41].

Toluene can be directed to chemical industries and laboratories, as it can be used as an additive in fuels, and as a solvent for paints, coatings, rubber, resins, thinners in nitrocellulose lacquers and adhesives [39,41,47,48].

Xylene alsohas applications in chemical industries and laboratories, being used as solvent and chemical precursor [39,41,47,48]. Limonene (1-methyl-4-isopropenil-cilohexene) similarly can be used in chemical industries and laboratories [39,41,47,48], with application as a biodegradable solvent and additive of fuels (up to 3% concentration). According to Danon et al. [65], at least 2.5 wt% of a steel-free tire can be converted to di-pentene.

Gas type GLP can be used as an energy source for feeding the pyrolysis process, whereas the excess could be stored in gas cylinders for sale [11,42,63]. In addition, carbon credits, whichexist in theory, could be obtained [55–57].

An additional source of profit could involve the application of a price to the collection of tires from tire resale companiesto eliminate their environmental liabilities [36,66,67]. According to Roy et al. [5], in USA, fees are charged to dispose tires, for which a value of US$1/tire is estimated, while, according to Lagarinos and Tenorio [16], in Brazil, this fee is US$ 0.45 /tire.

4. Conclusions

In the conditions described in this study, the yield of pyrolysis process was 41% pyrolytic oil, 38% carbon black, 12% gas and 8.9% steel scrap, with a calorific value of 36 MJ/kg of tire.The carbon black was composed of 90% carbon, which has higher quality than required by the steel and ink industries, and the pyrolytic oil was composed of 66% gasoline and 33% other oils, with sufficient quality to be used as an additive for fuels, or as fuel for engines and furnaces.The analysis showed that the resulting products, pyrolytic oil and carbon black, were within the standards established by Brazilian law and were similar or better than reported in the literature, enabling their use invarious industries.Moreover, it wouldturn usedproducts into raw materials that can be used invarious industries. The main products were carbon black and pyrolytic oil.

Revenue obtained from the sale of products generated by pyrolysis of tires was US$ 1.927 million and the total profit was US$ 1.312 million. It is noteworthy that the total profit could fully pay the costs to the company in the first year and that the total profit couldbe US$3.455 million carbon credits and energy were sold.

Thus, the environmental benefits of pyrolysis process of scrap tires include avoiding the disposal of tires directly into landfills and wasteland, thus avoiding the contamination of the soil, water, and air due to emission of chemical contaminants formed during the decomposition of the scrap tires. In addition, there is no need for the extraction of raw materials for the production of steel, fuel and carbon black produced in the scrap tire pyrolysis plant. The steel produced in the scrap tire pyrolysis plant is cleaner than the steel produced in the current modes. The carbon black produced in the pyrolysis process of scrap tires is cleaner than the currently marketed carbon black. The proposed method produces cleaner fuels than petroleum byproducts, and, as the pyrolysis process generates many products, the fuels have low cost. The use of gas and fuel oil from the tire pyrolysis process will supply part of the Brazilian population's need for these fuels. The recycling of scrap tires into fuel production may reduce the search for new oil fields. Other benefits result from the fact that, as the decomposition of the tires is via vacuum pyrolysis, there is no consumption of air, biotic or abiotic materials, and, as water is used only in refrigeration, it can be considered that water consumption is negligible. Since the plant feeds itself on energy, it does not influence the consumption of renewable sources to supply the needs of its production (the Brazilian energetic matrix is essentially from renewable sources). As all gases, liquids, and solids are not emitted into the environment, there will soon be no contamination of soil, air, and water derived from the plant of scrap tire pyrolysis process, and, consequently, the population neighboring the plant will have a good image of the company. By avoiding the release of greenhouse gases, the company will be a creditor of carbon credits, which will make the company environmentally friendly, and ultimately increase its client portfolio.

Other relevant findings arerelated tothe social benefits of pyrolysis process of scrap tires as follows: the collection of scrap tires for pyrolysis will reduce the volume of garbage that will be carried to the dumps and, consequently their costs, which may then be invested in other benefits to society.

In addition, the negative effects of scrap tire clusters on cities will be avoided. Pyrolysis plants do not release toxic or greenhouse gases, and thuswill not be responsible for the generation of respiratory diseases or climate change in cities of the region. As the plant cogenerates energy, the energy excess will help to supply the energy demand of surrounding cities. The generation of direct and indirect jobs in the city and region surrounding the tire pyrolysis plant will also contribute to the increase of the purchasing power of the people and consequently allow access to food, housing, and better healthcare and education. The increase in the flow of capital in the region will lead to an increase in trade in goods and services;with the increase of commerce, there will be an increase in tax collection and, therefore, municipalities may invest in improvements in public spaces, schools and hospitals in cities.The cities can also concentrate some of the taxes on the improvements of water distribution networks, and on the collection and treatment of sewage, thus improving their image and avoiding polluting the environment due to the scrap tire discard. With the increase in the purchasing power of individuals, the company will be contributing to the improvement in the quality of life of the residents of the surrounding cities; as the pyrolysis plant is a creditor of carbon, its products are derived from the recycling of a waste, soon it has a good image before society, as an ecofriendly company.

Thus, the company can gain with energy sale from cogeneration, due to the sale of 1600carbon credits and gains an image of ecofriendly company, which favors the marketing for selling its products. Overall, the viability for the proposed alternative for dealing with used tires will depend on the combination of the implementation of an efficient plant and recycling process, with the development of adequate marketing and supply chain strategies that allow for redirecting the resulting recycled products to utilizations that are able to extract value from them, and therefore provide an attractive return.

This work showed that tire pyrolysis is an innovative and ecofriendly process, offering a clean production that is economically viable andcan be used as a solution for the disposal of used tires in Brazil. As observed in [68], a largest benefit of pyrolysis is its ability to effectively dispose a type of waste that is hard to recycle while offering the possibility of obtaining recycled products that have economic value in several applications. The economic and environmental gains is relevant to promote the adoption of environmental practices [69–71].

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Development of Sustainable Recycling Investment Framework Considering Uncertain Demand and Nonlinear Recycling Cost

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Abstract: This paper presents a more active and efficient recycling investment strategy that considers the balances among the current production constraints, manufacturing profits, and recycling investments for a sustainable circular economy as compared to the current methods. While existing production planning has numerous uncertainties and nonlinear characteristics, the circular economy-based production planning constitutes more complex uncertainties and nonlinear characteristics that result from an uncertain return rate, demand uncertainties, and nonlinear return on investment costs. This paper suggests a stochastic nonlinear programming model-based active recycling investment framework so as to generate a more effective process plan to handle these characteristics. In the proposed framework, recycling investment strategies are quantitatively analyzed when considering uncertain demand and unclear production conditions. In addition, the effective solving techniques for the circular economy based production framework are obtained while using Monte-Carlo based sample average approximation and memetic algorithm. To prove the effectiveness of the proposed framework, it is implemented for a given system and the numerical analyses that were conducted for the various sustainable manufacturing scenarios.

Keywords: recycling investment strategy; demand uncertainty; Stochastic nonlinear Programming; Monte-Carlo based sample average approximation method; memetic algorithm

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1. Introduction

The circular economy among the leading contemporary economy trends considers the environmental issues and sustainability of the business. Its definitions and concepts have differed in most research studies, including Geissdoerfer et al. [1]. Based on the relevant research studies [1–3], the circular economy is defined as a closed-loop system, in which the production resources, environmental losses, and energy leakages are minimized. Various strategies and techniques have been proposed and implemented in order to minimize the usages and losses of these resources.

The usages and productions of refurbished products are all the representative activities of circular economy. The sales of refurbished products and their relevant supply chains activities are among the most frequently applied circular economy techniques. While many research studies have provided several effective remanufacturing/refurbishing processes and techniques, most of these studies have been limited in the domain of plants and the factory planning level. This shows that more expanded agendas (e.g., the investments and strategies for gathering recycling components) have been studied less comparatively. This paper provides a new and effective production planning framework that considers additional recycling investments strategies in order to overcome these issues. While the existing strategies (e.g., additional installment of collecting facilities, special promotion for the gatherings or recycling exchange compensation) may boost the collection of more recycling components, excessive investments might harm the corporate or business profits. This paper considers both the collection strategies and current production constraints in tandem with the proposed integrated framework.

The proposed framework characteristics are summarized while considering more vague uncertainties and the embedded nonlinearities. While a general process planning has several uncertainties, including unclear demand and supply abilities, the circular economy-based process planning should consider the more expanded uncertainties, together with the return rates of the recycling modules. Additionally, the prediction time horizon for the return rate is not aligned with the overall production planning time horizon. It results from the fact that the gathering of the recycling modules mainly depends on the number of products sold prior. Subsequently, its gathering pattern has the typical nonstationary characteristics. Moreover, the efforts for enhancing the return rate for obtaining a considerable number of recycling modules exponentially increase. This tendency can be through nonlinear cost functions of recycling investments.

This paper integrates these characteristics when considering the economic and environmental viewpoints through stochastic programming approaches. The embedded uncertainties are captured while using time-series data analyses and the relevant probabilities. Nonlinear profit and cost structures are modelled while using fitted nonlinear functions. The integrated model is a type of stochastic nonlinear programming models. A more effective and accurate solving method is required for the proposed framework, while numerous research studies provided effective solving techniques. In order to solve the circular economy-based process planning including the assertion of gathering investments for refurbished modules, this paper provides an integrated stochastic programming framework while using Monte-Carlo's sample average approximation and the memetic algorithm. The framework is implemented for a software program supporting circular economy-based production planning, so as to prove the effectiveness and solving techniques of the proposed framework. Its effectiveness is then tested through comparisons of the results under various scenarios and analyses in this study.

The following section presents the relevant background information and literature reviews. Section 3 describes the strategic decision framework and the mathematical model supporting the circular economy. Section 4 proposes the efficient algorithms for the suggested framework. Ultimately, its effectiveness is confirmed with the implementation of the framework and its numerical analyses in Section 5.

2. Background and Literature Review

Circular economy is a main stream economy concept that is being fronted by every government, municipality, and corporation, as highlighted in the previous section. Circular economy has emerged fast with cooperative movements and regulations, while similar concepts and activities have been discussed and implemented widely since 2000. Numerous research studies have defined the term Circular Economy (CE) and categorized it while using various concepts. Table 1 shows the recent CE concepts, keywords, and main ideas. These studies can be considered through integrations and modifications of the past former CE studies.

Table 1. Concepts and main ideas for Circular Economy (CE).

Research Studies	Main Concept for CE	Key Ideas for CE
Cullen [4]	- Conservation of the quantity of materials - Minimization of dissipative material losses	- Measurement of resources' circularity - Recycling of a recoverable end-of-life (EOL)
Boken et al. [5]	- Increasing product/material's circularity	- Challenges for exploiting intuitional opportunities
EMF [6]	- Enhancing circularity using six strategies	- Categorizing types of circular economy using "the butterfly diagram"
Ness and Xing [7]	- Synthesis of "closed-loop activities" and "optimized uses of assets"	- Necessity of integrated methodologies against shortcomings of the existing CE concepts
Hollander et al. [8]	- circular product design using "design for product integrity" and "design for recycling"	- Viewpoint in regards to "product design" concepts
Mendoza et al. [9]	- Integration of manufacturing and product design for enhancing CE	- A new Framework of Back-casting and eco-design for the circular economy (BECE)

While several studies have discussed the concepts and definitions of the circular economy, the next phase is on how to enhance the current CE. These issues are related to the detailed activities for CE. Ellen MacArthur Foundation (EMF) [6] used as a main referencing source for many CE research studies, categorizes these activities into six phases: Reuse, Repair, Refurbishment/Remanufacturing, Repurpose, and Recycling. Although the recycling method is the broadest CE activity among them, most of existing activities are too ineffective to generate an executable production planning. "Refurbishment/Remanufacturing" is focused more as the main CE activity in this paper, since this study focuses on an executable circular economy-based production planning.

Many research studies examined production planning frameworks on the remanufacturing processes. Savaskan et al. [10] provided a price strategy for a refurbished product and Kim et al. [11] developed a strategic pricing framework for a closed loop supply chain while using the remanufacturing process. Table 2 summarizes the characteristics of the current production planning frameworks in regards to the remanufacturing processes.

However, most of the research studies ignore investments and the relevant activities that enhance the product circularity. Existing research studies examine a production planning while using already recycled products or an estimation of the amount. While the additional investments for increasing return rate for End-of-Life (EOL) part are comparatively ignored, they establish mathematical programming models within fixed ranges of the returning rates. Consequently, the subsequent uncertainties (e.g., customers' uncertainty and modeling parameters) are modeled into fuzzy logic-based mathematical programming or nonlinear programming models. As described in the previous section, the existing studies fail to incorporate efforts for enhancing products' or modules' circularity in their production planning. In this paper, these strategies are classified as "passive investment strategies for remanufacturing". The efforts or investment to enhance return rates for EOL parts are needed in order to actively enhance CE. However, the bulk of the existing papers have ignored these efforts and their economic analyses. As a result, this paper suggests an integrated framework that simultaneously considers existing production constraints and investments for the refurbished product's circularity. For this concept, the proposed framework is classified as "active investment strategies for remanufacturing".

Table 2. Characteristics of the existing remanufacturing-based production planning frameworks.

Research Studies	Characteristics
Savaskan et al. [10]	- Consideration of three options (direction collection from customers, offer of incentives, collection using a third party) - Mathematical programming-based planning - Passive investment strategy for remanufacturing
Kim et al. [11]	- Price based modeling framework for a closed loop supply chain - Fuzzy logic embedded framework - Passive investment strategy for "remanufacturing"
Ghahremani-Nahr et al. [12]	- Uncertainty modeling using fuzzy logic - Fuzzy logic embedded mathematical programming model and an usage of "Whale-optimization method" - Ignorance of active investment for remanufacturing
Hashemi et al. [13]	- Aerospace remanufacturing application - Scenario analysis under various changes of "lead time" and "defect rates"
Pishvaee and Torabi [14]	- Bi-objective probability-based mixed integer programming - Fuzzy logic-based uncertainty modeling framework - Ignorance of active investment for remanufacturing
Turki et al. [15]	- Consideration of all life cycles of a product - Genetic algorithm-based nonlinear programming model - Passive investment strategy for remanufacturing
Shakourloo [16]	- Stochastic goal programming considering a returning rate of a EOL product - Passive investment strategy for remanufacturing

The quantifying efforts for computing the circularity have been attempted by a number of research studies. Cullen [4] provided a circularity measure with (1) based on the amount of the recovered EOL material.

$$\alpha = \frac{recovered\ EOL\ material}{total\ production\ demands} \tag{1}$$

Linder et al. [17] modified (1) while using the economic values as a product-level circularity measure. However, these research studies are limited by the fact that the efforts used to increase circularity are deeply disconnected with the production planning. This paper redefines circularity and integrates it with production planning. The detailed explanations are described in the following section. Figure 1 shows several efforts and methods for increasing the circularity of the refurbishing components.

As shown in Figure 1, there are different strategies that can be applied to enhance circularity in an overall production system. The installation of additional collectors, recycling centers, distribution centers, or service centers can enhance refurbishing components' circularity. Reike et al. [18] summarized several methods for increasing the circularity. Likewise, promotions and advertisement [19] can reinforce industrial ecology. However, these methods have different Return on Investments (ROI). Additionally, it is evident that the ROI of each investment has nonlinear characteristics for achieving the target circularity. Additionally, the investment planning time horizon has to precede the production planning time. These considerations make it more difficult to effectively generate a circular economy-based production planning.

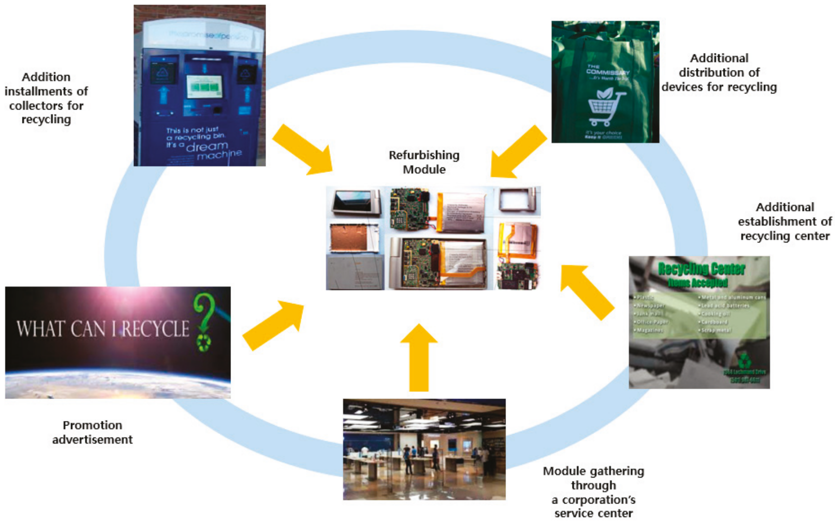

Figure 1. Methods of enhancing the circularity of the refurbishing components.

In regards to uncertainties, embedding on the circular economy is much broader when compared to those in a general production planning. The circularity rates and relevant uncertainties are entrenched more in the circular economy-based production planning while a general production planning handles several uncertainties from its demand and supply. This study simultaneously considers these uncertainties with stochastic and nonlinear characteristics.

The proposed model is based on an integrated stochastic nonlinear programming model to meet the economic and environmental planning goals. The stochastic programming model and its analyses are examined while using a number of research studies [20,21]. However, it is impossible to directly apply the existing studies' methods to the proposed framework, since the model in consideration has several demerits: information uncertainty, disparities in planning/investment time horizon, and nonlinear price characteristics. As a result, the following section provides a new and effective framework for maximizing corporate profits that simultaneously meets the criteria of high circularity.

3. Strategic Decision Framework and Its Mathematical Model Supporting Circular Economy

This section describes the overall proposed strategic decision framework for supporting circular economy. The targeted refurbished product is manufactured while using various components including: new parts, remanufactured parts, reused parts, and recycled parts. Figure 2 shows an example of a Bill of Material (BOM) for a refurbished product.

As shown in Figure 2, the refurbished product is manufactured and assembled while using various types of components, coupled with a variety of remanufacturing methods. This study also investigates the effective proportions of newly manufactured components and recycled components. The effective proportions of manufacturing components that were based on this research indicate that an efficient manufacturing BOM comprise of subcomponents with less production costs that meet the customers' needs. This paper is distinguished from other studies due to the consideration of gathering strategies while there are numerous related research studies on remanufacturing and recycling economy: extended advertisement, and additional installation of collecting facilities and incentive policies, as illustrated in Figure 1. While other studies only focus on the effective use of the already returned components, this paper considers the potential cost of returning components while using these investments. More collection may be achieved if these investments are effective, hence contributing more to circular economy. For this reason, the proposed framework is considered to be a more active strategy to support circular economy.

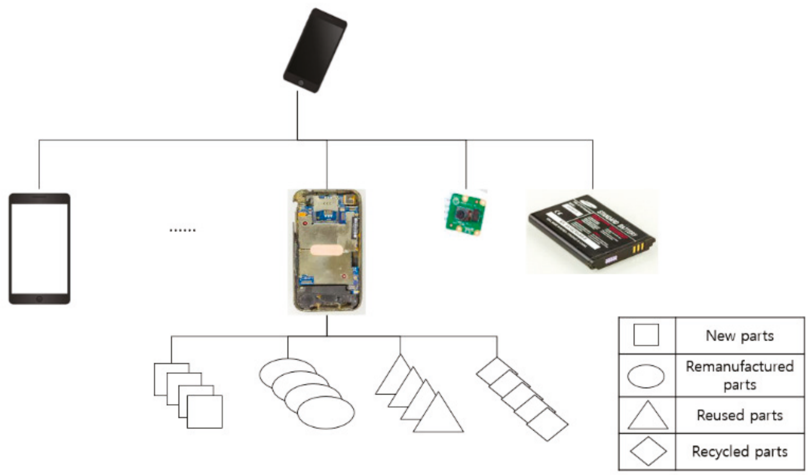

Figure 2. An example of a Bill of Material (BOM) for a refurbished product comprising of various subcomponents.

A refurbished product is comprised of several components or modules. A module is a newly manufactured part ($x_i^{I,t}$) or a refurbished component ($x_{i,j,k}^{II,t}$). Table 3 represents the descriptions of the detailed variables and parameters.

Table 3. Descriptions of decision variables and parameters.

Symbol	Description	Units	Decision Variable (d.v.)/Parameter (p)
$x_i^{I,t}$	The *ith* Components comprising of new part (I) in time period t	EA	d.v.
$x_{i,j,k}^{II,t}$	The *ith* Components with recycled parts (II) using "remanufacturing (j = 1) or reusing (j = 2) or recycling (j = 3) " method which is acquired from the kth investment.	EA	d.v.
$CM_i^{I,t}$	Manufacturing cost per each $x_i^{I,t}$ unit	Unit cost	p
$CR_{i,j,k}^{II,t}$	Refurbishing cost per each $x_{i,j,k}^{II,t}$ unit	Unit cost	p
$R_{i,j,k}^{II,t}$	The returned *ith* component with the *jth* remanufacturing method which is acquired from the kth investment at time period t	EA	-
D^t	The total demand of the product at time t.	EA	p
B_i	The number of the *ith* component in a product	EA	P
τ_k^t	The return rate of a product using the *kth* method at time t	$\tau_k^t \in [0, 1]$	d.v.
P^{II}	The price of a refurbished product	Unit cost	p
Cl_k	Investment cost for the *kth* method for increasing returning rate	Unit cost	p

Each component has a manufacturing cost per a unit ($CM_j^{I,t}$ or $CR_{i,j,k}^{II,t}$) in regards to its manufacturing types, respectively. While a completely new product only comprises of each $x_i^{I,t}$, a refurbished product comprises of several $x_i^{I,t}$' s and $x_{i,j,k}^{II,t}$' s. The required number of the *ith* module is represented as B_i in a product. When D^t is the customer's demand for a refurbished product at time *t*, the number of collected components ($R_{i,j,k}^{II,t}$) has to be considered. (2) denotes the constraints for meeting D^t.

$$x_i^{I,t} + \sum_j \sum_k x_{i,j,k}^{II,T} \geq D^t \cdot B_i,\ i \in M \tag{2}$$

The returned amount $R_{i,j,k}^{II,t}$ depends on the return rate τ_k^t. (3) denotes the relationship between $R_{i,j,k}^{II,t}$ and τ_k^t.

$$R_{i,j,k}^{II,t} = D^{t-\Delta t} \cdot \tau_k^{t-\Delta t} \cdot B_i \tag{3}$$

The usage of "$t - \Delta t$" denotes that the reused/remanufactured/recycled components are collected at time $t - \Delta t$ before meeting customers' demand at time t. As shown in Equation (3), it is reasonable that $R_{i,j,k}^{II,t}$ at time t is collected not from current customers' demand D^t, but from the previous consumed amount $D^{t-\Delta t}$. In this manner, Δt is interpreted as the returning time horizon of a products. Subsequently, (4) denotes the relationship between $x_{i,j,k}^{II,t}$ and $R_{i,j,k}^{II,t}$.

$$x_{i,j,k}^{II,t} \leq R_{i,j,k}^{II,t} \tag{4}$$

In general, a factory tends to produce the product using the refurbished or reused part with the constraint, $CM_i^{I,t} \geq CR_{i,j,k}^{II,t}$ if recycling parts exist. However, returned parts may be insufficient for meeting D^t ($D^t \cdot B_i > R_{i,j,k}^{II,t}$) in a general situation. While existing production plans attempt to use its new part in the situation, this study considers another alternative plan—efforts in enhancement of the return rates at planning time $t - \Delta t$.

The investment cost (Cl_k) is additionally needed when the *kth* investment is determined while using an effective strategy. In general, Cl_k is represented while using a nonlinear function of τ_k^t in (5).

$$Cl_k = g\left(\tau_k^t\right) \tag{5}$$

where $g(\cdot)$ is a nonlinear function

However, these investments consider additional efforts for collecting refurbishing products. It means that a certain constant amount at time t can be collected without additional efforts. (6) denotes this situation.

$$\tau_k^{t-\Delta t} = \hat{\tau}_k^{t-\Delta} + \alpha_k^{t-\Delta t} \tag{6}$$

The estimation of $\hat{\tau}_k^{t-\Delta}$ can be achieved by a number of statistical methods (e.g., time series analysis and other data mining methods) with the previous historical data. Section 4 provides the detailed estimation and analyses. Subsequently, (5) is substituted by (7) in this manner.

$$Cl_k = f\left(\alpha_k^t\right) \tag{7}$$

Figure 3 shows an example of a nonlinear function explaining the relationship between Cl_k and α_k^t. As shown in Figure 3, each k means an index that represents each investment (1: advertisement, 2: additional installment of collecting facilities, and 3: incentive policy).

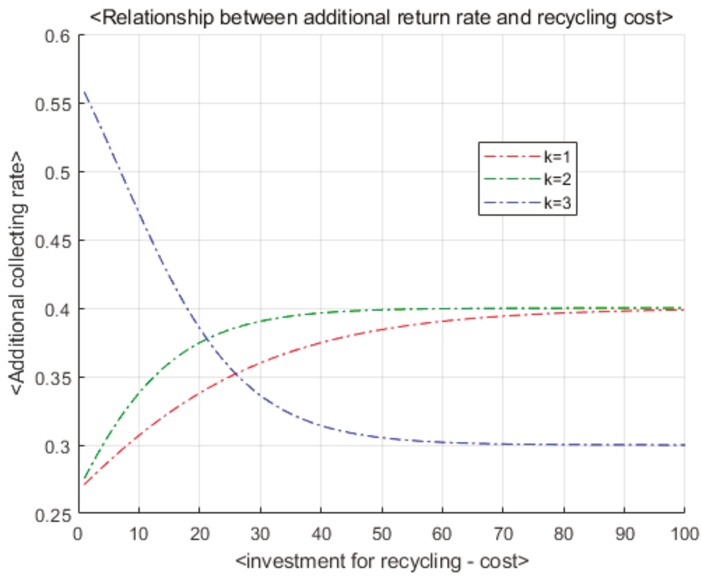

Figure 3. An example of a nonlinear function between $\mathrm{Cl_k}$ and τ_k^t.

This research focuses on the effective gathering investment strategy while considering the existing returned volume, the predicted return rates, and an estimated demand. The demand ($\mathrm{D^t}$) is determined while using previous market data and forecasts. Since various uncertainties are embedded in its prediction, it is only rational that the demand be represented while using a probability density function. Figure 4 shows the estimated $\mathrm{D^t}$ that is represented using a probability distribution.

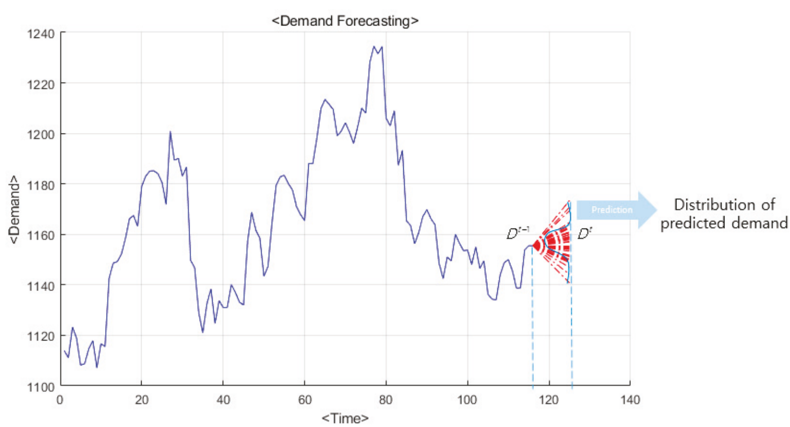

Figure 4. Estimation of $\mathrm{D^t}$ using a probability distribution.

The Formulas (2)–(7) are used as constraints in determining the effective manufacturing strategy for a refurbished product. The objective (8) of the decision at time t is to maximize the profit while considering the difference in price of the product and the overall production cost.

$$\max\ [P^{II} \cdot D^{t} - \sum_{i=1}^{m}\left(CM_{i}^{I,t} \cdot x_{i}^{I,t} + \sum_{j}^{n}\sum_{k}^{o} CR_{i,j,k}^{II,t} \cdot x_{i,j,k}^{II,t}\right) - \sum_{j=1}^{m} Cl_{k} \cdot D^{t-\Delta t} \cdot \alpha_{k}^{t-\Delta t}] \quad (8)$$

The mathematical programming model provided is categorized as a stochastic nonlinear programming model. The model has the characteristics of a stochastic programming model since D^t is represented while using a probability distribution. Additionally, the model has nonlinear terms from (7) and (8). Consequently, several parameters that are embedded in the model have to be estimated through statistical analyses. Figure 5 illustrates the overall procedures for the proposed effective production planning.

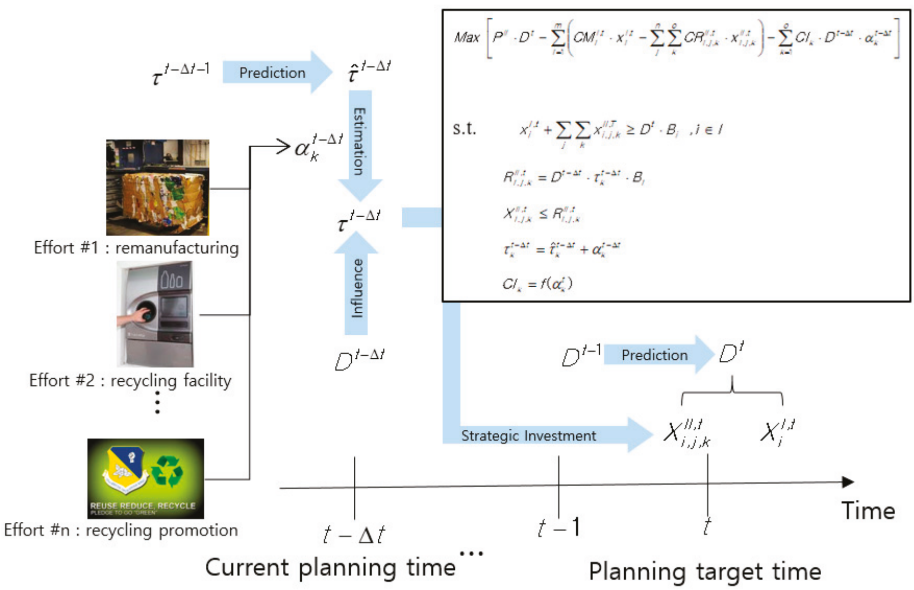

Figure 5. Overall procedure of the proposed framework.

The following section illustrates the detailed methodologies that are applied in solving the proposed model.

4. Parameter Estimation and Analysis Using Stochastic Nonlinear Optimization

As highlighted in the previous section, the proposed mathematical model shares the characteristics of a stochastic nonlinear programming. Moreover, statistical analyses have to be satisfied in advance as the prerequisite determinations for estimating the parameters D^t and $\hat{\tau}_k^{t-\Delta}$. This study uses a time-series based method to approximate the model parameters.

Figure 6 shows a flow diagram for implementing the proposed circular economy-based process planning. The accurately predicted demand (D^t) and the collecting volume ($\hat{\tau}_k^{t-\Delta}$) heavily influence on the solutions and analyses of the proposed model. The estimations of D^t and $\hat{\tau}_k^{t-\Delta}$ are estimated while using the current manufacturing plans and data, and are mainly driven using a time series technique. This research utilizes Autoregressive Integrated Moving Average (ARIMA) method or other nonlinear prediction methods for covering nonstationary data. The analyses of many research studies [22–24] assumes that most of the production demands and manufacturing related tendencies follow the nonstationary stochastic characteristics. Although $\hat{\tau}_k^{t-\Delta}$ can be monitored or directly estimated while using one of those methods, D^t is predicted using several existing time-series methods that enhance the accuracy of these estimations. These values are then represented while using a random variable ξ following a Gaussian distribution $N(\mu, \sigma^2)$. Both parameters μ and σ are estimated while using the predicted results from several time-series methods. Instead of the single value-based prediction, the application of this probability distribution enhances the representation power of the estimated demand. D^t can then be replaced with (9) while using a stochastic programming through recourse model with the bounds.

$$D^t \Rightarrow E[\min(q, \xi)\ ] \quad (9)$$

where $q = \min(\frac{x_i^{I,t} + \sum_j \sum_k x_{i,j,k}^{II,t}}{B_i}, i \in M)$.

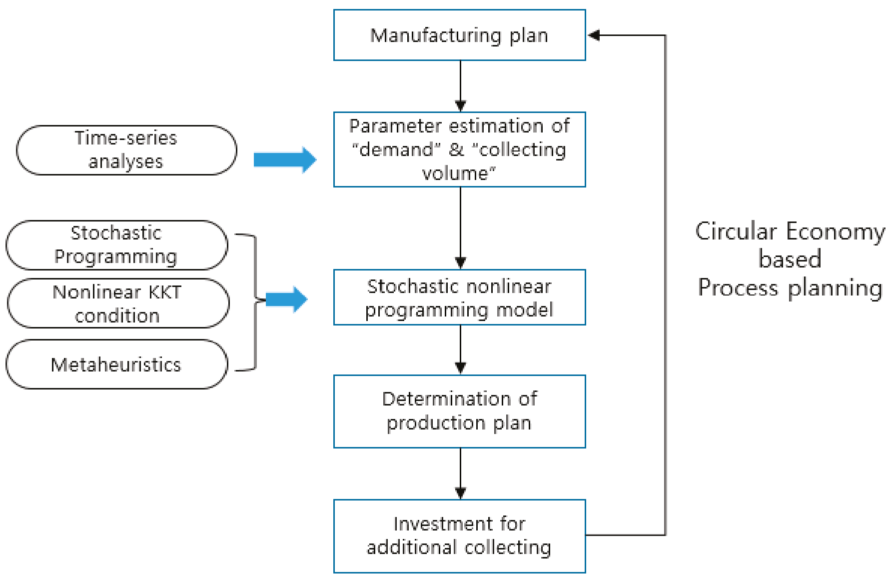

Figure 6. Flow diagram for implementing the proposed circular economy-based process planning.

As shown in the objective function (10), the mathematical model is categorized as a two-stage stochastic programming with the recourse model.

$$\max\ [P^{II} \cdot E[\min(q, \xi)] - \sum_{i=1}^{m}\left(CM_i^{I,t} \cdot x_i^{I,t} + \sum_j^n \sum_k^o CR_{i,j,k}^{II,t} \cdot x_{i,j,k}^{II,t}\right) - \sum_{k=1}^{o} f\left(\alpha_k^{t-\Delta t}\right) \cdot D^{t-\Delta t} \cdot \alpha_k^{t-\Delta t}] \quad (10)$$

In the case that a nonlinearity condition (7) is excluded, a general method of applying the stochastic transformations and KKT conditions [20] can be used, owing to its near-optimal solution. However, the existence of the provided conditions results in the difficulties in determining the global minimum from the recourse model. In order to overcome this discrepancy, many research of the studies, including Sakalauskas [25] and Shapiro [26], provided the Monte-Carlo based stochastic nonlinear programming solving—Sample averaging approximation (SAA) method. This paper applies the SAA method to generate more effective solutions. However, the solutions that were obtained using SAA method [27] are compared with different criteria, such as unbiasedness, consistency, and convergence. According to Shapiro [28], (9) can be replaced with (11), where p_i is the probability for ith scenario.

$$E[\min(q, \xi)] = \sum_{i=1}^{k} \min(q, \xi_i) \cdot p_i \tag{11}$$

where ξ_i is the i*th* sample from $N(\mu, \sigma^2)$

Subsequently, (12) is driven by the Law of Large Numbers [29].

$$\frac{\sum_{i=1}^{N} \min(q, \xi_i)}{N} \rightarrow E[\min(q, \xi)] \text{ w.p. } 1 \tag{12}$$

It can be easily ascertained that the estimator $\frac{\sum_{i=1}^{N} \min(q, \xi_i)}{N}$ is the unbiased and consistent estimator of $E[\min(q, \xi)]$, as each ξ_i is an *i.i.d.* sample and driven from Gaussian distribution $N(\mu, \sigma^2)$. The sample size N is determined while using the empirical test following the criteria (13) In order to support the convergence condition of the estimator, where ϵ, α, and δ are the parameters from Kleywegty et al. [30].

$$N \geq \frac{3\sigma^2}{(\epsilon - \delta)^2} \ln\left(\frac{\xi}{\alpha}\right) \tag{13}$$

(12) and (13) make it possible to solve the proposed model while using the Monte-Carlo based SAA method. The remaining issues include the handling of the nonlinear conditions and the terms resulting from (7). These issues can be addressed while using memetic based metaheuristics [31]. The memetic algorithm [32,33] is a type of metaheuristics method that combines the current metaheuristics and local searching techniques. While metaheuristic algorithms attempt to discover more solutions that are more improved when compared to the current local optimum, they are limited in regards to their searching efficiencies, such as solution accuracy and convergence. In general, the obtained quality of a local solution using metaheuristics is less than the quality that was obtained while using the heuristics method with the same input range. The local optimum searching method is combined with a metaheuristic algorithm in order to overcome these limitations. In a memetic algorithm, an alternative solution is realized while using an optimization method. It guarantees the quality of the calculated local solution within its local range. Consequently, the local solution is morphed into a better solution while using a metaheuristic. Neri and Cotta [34] summarized the existing literatures using memetic algorithms. Numerous applications and research studies, including the one by Neri and Cotta [34], use several memetic algorithms that combine various local search methods and metaheuristics to find finding more efficient parameters or solutions. This paper applies a memetic method for finding more efficient investment strategies, which supports circular economy. The applied memetic method utilizes a gradient searching technique in place of the local searching and a Genetic Algorithm as a metaheuristics method. Choo and Lee [35] applies the similar memetic learning framework to determine the parameters in a deep learning machine.

As a local searching method, this study uses a KKT based gradient method. Each constraint ((2)–(6)) is combined to (10) with each Lagrange multiplier. Subsequently, each decision variable's update is achieved while using the driven Lagrange function $L\left(x_i^{I,t}, x_{i,j,k}^{II,t}, \alpha_k^{t-\Delta t}\right)_{i\in M,\ j\in J,\ k\in K}$ and each differential $\frac{\partial}{\partial\phi} L\left(x_i^{I,t}, x_{i,j,k}^{II,t}, \alpha_k^{t-\Delta t}\right)$, where ϕ is a decision variable.

$$x_i^{I,\,t'} \leftarrow x_i^{I,t} + \eta \cdot \left(\frac{1}{B_i} - CM_i^{I,t} + \lambda_{(1)}^{i}\right) \tag{14}$$

where $\lambda_{(1)}^{i}$ = a Lagrange multiplier for the constraint type (2).

and, η = a step length

$$x^{\text{II},\,\text{t}'}_{i,j,k} \leftarrow x^{\text{II},\text{t}}_{i,j,k} + \eta \cdot \left(\frac{1}{B_i} - CM^{II,t}_{i,j,k} + \lambda^{i}_{(1)} \right) \tag{15}$$

(14) and (15) denotes the learning procedures for each production and returning component, respectively. Similarly, (16) denotes how each investing strategy is learned for the more effective circular economy.

$$\alpha_k^{\text{t}-\Delta\text{t}'} \leftarrow \alpha_k^{\text{t}-\Delta\text{t}} + \eta_\alpha \cdot \left(\lambda^{k}_{(5)} \frac{1}{B_i} - \frac{\partial f\left(\alpha_k^{\text{t}-\Delta\text{t}}\right)}{\partial \alpha_k^{\text{t}-\Delta\text{t}}} \cdot CI_k \cdot D^{t-\Delta t} \right) \tag{16}$$

The usages of different step sizes (η and η_α) result from the different resolutions of the decision variables $x_i^{\text{I},\text{t}}$, $x^{\text{II},\text{t}}_{i,j,k}$, and $\alpha_k^{\text{t}-\Delta\text{t}}$. The more improved solution is attempted using the Genetic algorithm (GA) when a local optimum is arrived using (14), (15), and (16). The genotype conversion is achieved using the binary number conversion from a decimal number. For instance, an initial value of a decision variable $x^{\text{II},\text{t}}_{i,j,k}$ is obtained while using (17) and a randomly generated number r.

$$x^{\text{II},\text{t}}_{i,j,k} \leftarrow \text{r} \cdot \left(\frac{D_t}{B_i} - x_i^{I,t} - \sum_{l}^{N} \sum_{m}^{o} x^{II,t}_{i,l,m,l\neq j,m\neq k} \right) \tag{17}$$

The generated decimal value is converted into the corresponding binary value. Afterwards, crossover is achieved while using Single-point crossover [36]. The mutation is achieved with a conversion (0→1 or 1→0) of its binary value in a randomly determined position. This position is determined using (18), where B(n) is the binary representation of the decimal value n and d(n) is the digit number of n.

$$\left\lfloor d\left(B\left(\frac{D_t}{B_i} - x_i^{I,t} - \sum_{l}^{N} \sum_{m}^{o} x^{II,t}_{i,l,m,l\neq j,m\neq k} \right) \right) \cdot r \right\rfloor \tag{18}$$

where $\lfloor n \rfloor$ = the rounded-off value of n.

Table 4 shows the applied Genetic algorithm procedure in this research. The provided algorithm has four parameters: *th*, *p*, *r*, and *m*. *th* is a threshold value specifying the termination criterion of the algorithm. *p* is the number of the tested solutions in each GA iteration. *r* is the fraction of the solution set that is to be replaced by the crossover operation and *m* indicates the mutation rate.

Table 4. The applied Genetic Algorithm.

	Algorithm: Genetic Algorithm (*th*, *p*, *r*, *m*)
1	Initialize the values of the decision variables using (17)
2	Evaluate each constraint from (2) to (6)
3	if (constraints is met)
4	go to *Line 8*
5	else
6	go to *Line 1*
7	end
8	Evaluate the objective value using (10)
9	While (gap between the objective values > *th*)
10	select $\lvert(1-\mathbf{r})\cdot\boldsymbol{\rho}\rvert$ members from Line 1
11	crossover $\left\lvert\frac{r\cdot\rho}{2}\right\rvert$ pairs using *Single-point crossover* from Line 10
12	Mutate $\lvert\mathbf{m}\cdot\boldsymbol{\rho}\rvert$ using (18) number of members
13	Sort with (9) in descending order
14	Select $\lvert\boldsymbol{\rho}\rvert$ solutions
15	end

The overall solution procedure for the proposed model combines the Genetic algorithm that is shown in Table 4 with the gradient based local searching provided in (14), (15), and (16). During these processes, $E[\min(q, \xi)]$ is projected while using the sample averaging approximation method. The mathematical model provided and the stochastic nonlinear programing based method contributes to the estimation of effective collecting strategies. As the reputation of circular economy grows more and more, production/collection quantities and related BOM portions become crucial decision factors. The relevant collecting investments, together with their budget strategies, have to be considered in this model. The proposed framework is considered as an effective remanufacturing in support of the circular economy. The ensuing section describes the developed remanufacturing systems and its numerical studies' analyses.

5. Development of Remanufacturing Framework and Its Numerical Analysis

This section describes the implementation of the proposed framework and the numerical analyses while using the proposed software program. The system includes several information/parameter panels and three graph windows. Table 5 represents the roles and functions of each panel/windows.

Table 5. Roles and functions of each panel and window.

Type	Roles	Organization	Functions
Window	Demand forecasting	- Demand plot	- Plotting the demand data - Analyzing data - Output: Gaussian dist.-based predicting demand
Window	Return rate estimation	- Plot of existing Return rate	- Monitoring return rate - Capturing return rate for circular economy-based production planning
Panel	Main information	- Number of BOM components - B_i	- Specifying BOM and related information - Editing with the real data
Panel	Price information Setting	- Price of a refurbish product - newly manufacturing cost per module - recycling cost per module	- Specifying price information - Editing with the real price data
Panel	Investment strategy information	- number of investment strategies for circular economy - each investment cost/product	- Specifying information for investment strategies - Nonlinear equations can be embedded in the system - Editing with user data
Panel	Memetic algorithm parameters	- Parameters for local search - Parameters for metaheuristics	- Setting parameters for the gradient descent search methods - Setting parameters for Genetic algorithm
Window	Solution	- plots of objective function values	- Showing trends of the objective function

Table 6 shows an analyzed numerical example to illustrate the effectiveness of the proposed framework.

Table 6. Data and Parameters for a case study and its analyses.

Type	Values
Input	- Number of BOM modules: 6 - B_i = [2,1,1,1,2,1] - $CM_i^{I,t}$ = [250, 500, 1750, 2000, 2250, 1750] - $CR_{i,j,k}^{II,t}$ = [0, 0, 600, 500, 500, 450, 0, 0, 600, 500, 500, 450, 0, 0, 600, 500, 500, 450, 0, 0, 600, 500, 500, 450] - Cl_k = [214 389 357 429] - τ_k^t = 0.4 / - $D^{t-\Delta t}$ = 8450
Parameters	- Local search iteration number: 10,000 - η = 0.01 / - η_α = 0.1^10 - th = 0.0001 / - p = 10 / - r = 1/6 / - m = 0.2
Initial solutions	- $x_i^{I,t}$ = [0,0,0,0,0,0] - $x_{i,j,k}^{II,t}$ = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0] - $\alpha_k^{t-\Delta t}$ = [1,1,1,1]

The current return rate data and historical demand data in the customized formats are read in the system after inputting the initial solutions and parameters in the developed system. These data is then plotted and analyzed, as shown in Figure 7.

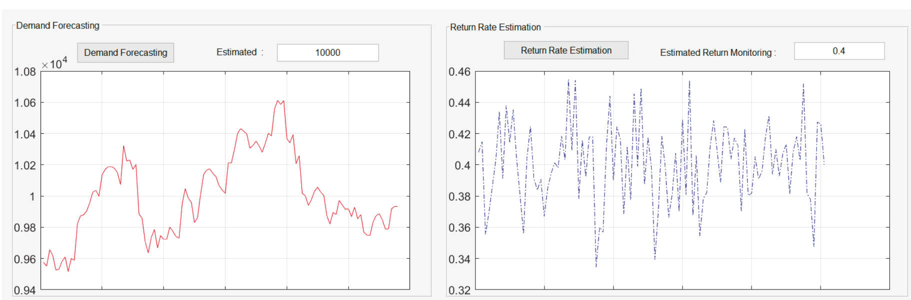

Figure 7. Forecasted demand and estimated return rate.

As shown in Figure 7, the data is analyzed while using various time-series methods. The best fitted model in this scenario is proven to be the ARIMA (3, 1, 2) model and the prediction is presented while using a Gaussian distribution $N\left(10,000\ ,\ 23^2\right)$. In addition, the current return rate is estimated to be 0.4. Consequently, to generate the solution of the suggested mathematical programming model, the parameters of the memetic algorithm are inputted to the system.

The solution is then generated and the changes of the objective values plotted, as shown in Figure 8.

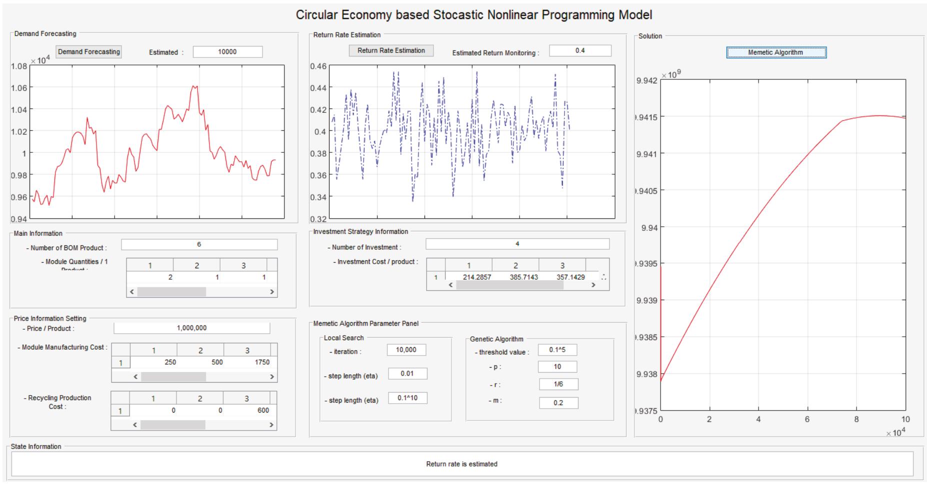

Figure 8. The execution of the process planning and investment framework supporting circular economy.

As illustrated in Figure 8, the objective function value is enhanced and converged to a near-maximum value while using the proposed memetic algorithm. The generated solution supports the circular economy in regard to the fact that the production plan pursues more gathering of recycling components while considering business profits. In addition, it reduces the environmental pollutions due to the use of recycling components.

The solution (Case III) is compared with the other cases to prove the effectiveness of the proposed framework: the case that ignores refurbishing (Case I) and the remanufacturing case barring additional returning investments (Case II). Table 7 provides these solutions and comparisons.

Table 7. The comparisons among three remanufacturing scenarios.

Comparisons	Case I	Case II	Case III
Main scenario	- production depends on "newly manufacturing components" only	- Using "reusable modules" - additional returning efforts are ignored	- additional investments are considered
Profit (under the scenario in Table 6)	$9.89 * 10^9$	$9.91 * 10^9$	$9.94 * 10^9$
Number of Manufacturing components	[2000,1000,1000,1000, 2000,1000]	[2000,1000,699,699,1269,699]	[2000,1000,355,355,432,355]
Number of Recycling components	N/A	[0,0,301,301,731,301]	[0,0,137,173,434,137,0,0,148, 148,434,148,0,0, 53, 53,266, 53,0,0,355,355,434,355]
Usage rate of recycling modules	-	40%	82.91%
Returning rate per each investment strategy	N/A	N/A	[0.2189,0.0741,0.0982,0.0379]

The case with additional returning efforts has the largest profit in addition to the largest utilization rate of recycling modules, as shown in Table 7. Based on the analyses, the third scenario that applies the proposed framework has twice the recycling modules keeping the maximal profit compared to the second case. Additionally, it is inferred that the third case might contribute to sustainable manufacturing while using less energy as a result. These results can be differ based on the assumed conditions and parameters. However, the proposed model and the solving framework are considered as effective production planning framework that supports circular economy with regards to the additional investment strategies for increased collection, which are evaluated quantitatively under stochastic and nonlinear business environments.

6. Conclusions and Further Studies

The circular economy is among the representative trends leading contemporary society. As more efficient business techniques and management methodologies evolve for maximum corporate profits, there has been growing concerns regarding the preservation environments for the future generation, leading to growing with the governmental and municipalities' regulations. These trends have a lot of terminologies, including the circular economy, sustainable engineering, and closed-loop SCM. This paper concentrates on the more active and detailed production planning that supports circular economy. In particular, more focus is put on the decision making for additional investment strategies for recycling products collection. There are existing portfolios for investment strategies, such as promotions, additional installments of gathering facilities, and/or other incentive policies. Existing production planning constraints have to be considered, although these tasks could guarantee more returns of recycling components.

The majority of the circular economy environments have more uncertainties when compared to existing contemporary economies. The uncertainties in returning amount and qualities of recycling modules are also embedded, despite existing contemporary economies having uncertainties in demand and supply abilities and production parameters. Consequently, the circular economy-based production planning has to reflect on the existing planning constraints, additional investments, and more piled uncertainties. This paper proposes a stochastic nonlinear programming model-based production planning framework to solve these issues. In the proposed framework, the demand information is captured through a probability distribution. In addition, the uncertain return rate and the costs of recycling components are represented while using nonlinear function. It is difficult to obtain the exact solution set that meets the circular economy criteria because the framework consists of stochastic and nonlinear characteristics. As a result, this paper presents new and efficient techniques, such as the sample averaging approximation method based on Monte-Carlo method and the memetic algorithm. The use of the Monte-Carlo based sample averaging approximation method helps to handle the uncertainties that are embedded in the circular economy environment. Consequently, the mathematical model is transformed into a Lagrange function while using nonlinear K.K.T. conditions. To generate effective solution sets for the function, the memetic algorithm, which combines Gradient based local search and Genetic algorithm, is utilized. The framework is implemented in a software program supporting circular economy-based production planning in order to prove the effectiveness of the proposed framework in addition to its solving techniques. Thus, its effectiveness is proven through the comparisons of results under various scenarios and analyses. While the proposed framework considers recycling investment framework with uncertain demand and nonlinear recycling cost, this research ignores the suggestion of detailed investment strategies, such as additional network generation or activities for extra efforts. The proposed framework handles these features only in regards to nonlinear costs. Additionally, this research ignores the current integrations of the environmental effects and environment assessments. It is considered that the effectiveness of the proposed framework is enhanced when these assessments are integrated.

As further studies, the broader expansions of the proposed framework are considered. The production planning framework presented particularly focuses on the existing production parameters and extra efforts in the enhancement of the returning rate. The framework covering the overall lifecycle of its supply chain networks is necessary while the current framework handles production planning.

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Additive Manufacturing: Exploring the Social Changes and Impacts

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Abstract: Despite the myriad of possibilities and applications of additive manufacturing (AM) technology, knowledge about the social impacts of this technology is very scarce and very limited in some areas. This paper explores how factors generated by the development of AM technology may create social impacts, affecting the health and social well-being of people, quality of life, working conditions, and the creation of wealth. This paper presents the results of an exploratory multiple case study conducted among four Portuguese organizations that use AM technology, aiming to determine their perceptions regarding the social impacts of AM, its effects, and causes. The results confirm that AM technology is mainly seen to create positive impacts on health and safety (regarding physical hazards), on expectations for the future, on leisure and recreation, on low disruption with the local economy, on economic prosperity, on the professional status, and on innovative employment types. Nevertheless, a negative impact was also found on health and safety (concerning hazardous substances), as well as several mixed and null impacts. The main limitations of the research arise from the use of a case study methodology, since the results can be influenced by contextual factors, such as the size of the organizations in the sample, and/or social, cultural, technological, political, economic, and ecological factors. This study gives an up-to-date contribution to the topic of AM social impacts and social changes, an area which is still little-explored in the literature.

Keywords: additive manufacturing; social change; social impacts; 3D printing; rapid prototyping

1. Introduction

The introduction of additive manufacturing (AM), better known as 3D printing, emerges as a disruptive technology that seems to bring with it several changes and impacts to the traditional product lifecycle, conveying new challenges to business models and society in general. AM technology emerged in the 1980s, through the work of Charles Hull [1,2], in stereolithography. Nowadays, this technology is used in several industries to describe an additive process where material is added layer-by-layer to create physical prototypes, parts of products, or a final product, directly from digital data [3,4]. This technology contrasts with the traditional manufacturing methods which use subtractive processes to remove material from a slab of raw material. Many processes use "layer manufacturing", and the literature identifies this technology with different denominations, such as 3D printing, additive fabrication, layered manufacturing, direct digital manufacturing, and rapid prototyping.

According to Attaran [5], AM enables innovation and the making of low-cost prototypes and mock-ups with a reduction of time. It allows the use of a wide variety of different materials, such as plastics, resins, metals [6,7], glass, ceramics, powders, and rubbers, among others, which can be applied to various geometries [3,8]. The increasing use of AM in small and tailored productions, enabling customization and more competitive prices [9], is changing business models, bringing with it unpredictable impacts for business rules and society [10–12], and this increasing use could have the potential for degrowth [13,14]. All these factors result in social impacts and changes which are still unknown.

The literature on the social impacts of AM is scarce, making further research on the matter essential [15,16]. Apparently, the social impacts of AM technology are related to job losses [15], intensity of work, employment schemes and types of work, and the development of new skills [11,17]. Social impacts on health and safety at work have also been identified in the literature [15,16]. The increase of population well-being, associated with an increase in life expectancy and quality of life, resulting from AM applications in medicine, is pointed out as a significant social impact [11,17]. Therefore, research on the impacts of AM in real case settings is necessary to anticipate future social impacts. This paper proposes to address this research gap. Four case studies within Portuguese organizations were developed to provide insights into the social impacts of AM. The present study is guided by three research questions:

- RQ1: What are the causes of AM social impacts?
- RQ2: What types of social impacts are expected?
- RQ3: Do they have a positive or negative effect(s)?

2. Background

2.1. Additive Manufacturing

A growing number of companies and new business models based on AM processes are emerging, creating enormous opportunities for the economy and society [18–20]. This technology is used by two groups of companies, those that use low-cost, low-end technologies, and those that use high-end technologies in cutting-edge sectors, such as in biomedical sectors, nanomanufacturing, [21,22] or bioprinting, also known as 4D printing [23].

A significant amount of research has been published on AM technologies, regarding their physical and chemical behaviours, as well as their economic and environmental impacts. These studies proclaim several AM-related advantages, such as (a) design flexibility with complex geometries [5,11,15,21,24], (b) reduced “time-to-market” [5,25], (c) design for customization [26,27], (d) reduced environmental impacts [11,24,28,29], and (e) higher profit due to customer specific solutions [5,15].

However, little is known about the social impacts of AM, and the few studies available on the topic make it harder to understand the matter [11,15,16]. These studies pinpoint several social impacts areas, as can be observed in Figure 1.

The impact of AM on intellectual property rights and policy is not clear [17,30,31], since new forms of intellectual capital property are emerging, such as creative commons licenses, license sharing, or the open source concept [17]. As has happened before with movies, music, and books, traditional forms of protection (e.g., design patents or copyright) might change. AM technology requests new forms of protection and respect for legal rights [17,31].

AM is changing established business models and markets [11,17], namely in terms of product customisation [10–12], the reconfiguration of supply chains [32], the extension of the product life [10,11], the reorganization of logistic systems (i.e., local production models [22]), and the potential for repair, remanufacturing, and refurbishment [10,11]. The possibility of consumers creating and co-designing their very own objects using printers at home, or by easily accessing them, can also change purchasing behaviours, resulting in impacts on society [17,22,33].

The social impacts of AM on education depend on the integration strategy into educational systems [34,35] and on the maturity and gaps of those systems [15]. AM technology brings new challenges, and its impacts on skills and education requirements remain to be studied [17,36,37]. This technology presents high potential, especially for engineering training [34,38], since it allows the use of physical prototypes for educational objectives [39–42], for the "Teaching Factory Concept" [43], and as part of research efforts in universities [36].

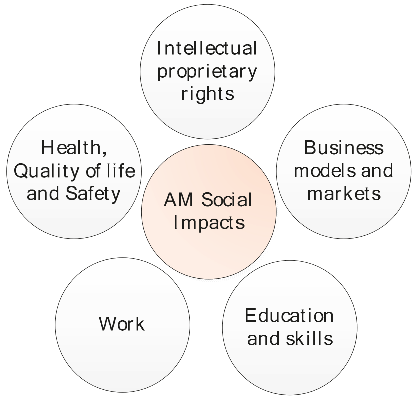

Figure 1. The areas of social impact for additive manufacturing (AM).

The literature provides some evidence of AM technology's social impacts on work and labour conditions. The apparent "clean" aspect of AM causes little preoccupation about individual safety, caution around the handling and disposal of materials, and consideration of a proper location for the equipment [16]. Other authors refer that AM technology can create unemployment and political destabilization in some economies, leading to changes in labour intensity, employment schemes, types of work, work conditions, working hours, working places, and employment policies, or even in changes in labour laws [15,25,44]. Conversely, positive impacts are foreseen, such as digipreneurship (digital entrepreneurship), allowing the creation of niche markets, access for people without prior knowledge of design and/or production to create diverse product types, and avoiding the need to go to work to big cities, among other social innovations related to the easy self-use and flexibility of AM technology [3]. The adoption of AM technology is also mentioned as positive to "especially aging societies, (that) might benefit from the ability to produce more goods with fewer people while reducing reliance on imports" [28].

The reduction of health costs for the elderly and the rise of life expectancy and quality are mentioned in the literature as AM social impacts [16,28], mainly because of the possible customizations of healthcare products (e.g., surgical implants, orthodontics, etc.) [11,20]. Several authors warn of the terrorism dangers associated with AM technology, as weapons production (i.e., guns, bullets, bombs, etc.) can be facilitated using the technology [28,45–47].

2.2. Social Impacts Definition

There is widespread consensus that social impacts are relevant and should be considered as part of the analysis of sustainability [48]. In the literature, despite recent advances [49], there is still insufficient knowledge regarding social impact assessment (SIA), namely on conceptual and theoretical issues [50–53].

There is no unanimity on the concept of "social impact" and its formal definition, which makes it difficult to distinguish social impacts from social changes, or even from societal impacts. Thus, some authors use the concept of social impact while others use social change to identify the same idea [16,54–56]. Also, the term "societal impacts" is used to refer to social impacts [15]. Several definitions of social impact are proposed in the literature [57,58]. A literature review of 50 papers [59] concluded that changes, which entail effects, cause social impacts. Some of these changes cause phenomena experienced by stakeholders and are recognized as social impacts. This definition, by being so broad, does not allow a crystal-clear identification of the concept of "social impact". To clarify the concept, the following subsections contain the definition of social impact, according to widely accepted operational guidelines/frameworks and Vanclay's [54] research.

2.2.1. Social Impact Operational Guidelines/Frameworks

The United Nations Environment Programme (UNEP) guidelines define social impacts as "consequences of positive or negative pressures on social endpoints (i.e., the well-being of stakeholders)" [60]. Social impacts are understood to be "consequences of social relations (interactions) weaved in the context of an activity (production, consumption or disposal), and/or engendered by it, and/or by preventive or reinforcing actions taken by stakeholders (e.g., enforcing safety measures in a facility)" [60]. The term social impact does not include the social change processes.

The UNEP Setac Life Cycle Initiative [60] proposes the use of the social life cycle assessment (S-LCA) methodology to assess social impacts along life cycle stages, considering five categories of stakeholders: Workers/employees, local communities, society, consumers (covering not only the end-consumers, but also the consumers), and value chain actors. This S-LCA approach is aligned with ISO 14040 [61] and ISO 14044 [62], and is well-accepted among professionals and researchers. The problem lies in the difficulty to quantify social impacts in contrast with environmental ones [63], and the scarcity of databases with accessible information concerning them [60].

The Global Reporting Initiative (GRI) [64] is a widely accepted sustainability framework to report social impacts [15,58,65], because it standardizes enterprises' reports on environmental, social, and economic aspects. This reporting system [64] presents 19 categories of social indicators, ranking the indicators as core (i.e., obligatory) or additional, and many of them are qualitative or binary (i.e., "yes" or "no"). This quantification bias makes it difficult, if not inhibiting, to quantify the indicators and comparisons [58].

The International Association of Impact Assessment (IAIA) [66] differentiates between social change process and social impact, because not all social changes cause social impacts. The claim that social change is (any) process affecting people, and the social impact is any experienced effect [56]. Despite the distinction between them, the definitions broadness hinders the quantification of the experienced effects.

2.2.2. Vanclay's Theoretical Framework

Vanclay [54,67,68] established the theoretical foundations of SIA. He discusses in detail the problem of the distinction between social change process and social impacts:

- Social impacts are "experienced or felt in either corporeal or perceptual terms" [54]. They "will vary from place to place, from project to project, and the weighting assigned to each social impact will vary from community to community and between different groups within a given community" [54]. This is a broad concept comprising all aspects that affect people directly or indirectly in one or more of the following topics: People's way of life, their culture, their community, their political systems, their environment, their health and well-being, their personal and property rights, and their fears and aspirations. Vanclay [67] argues that "direct social impacts result from social change processes that result from a planned intervention" and that "indirect social impacts are a result of changes in the biophysical environment".
- Social changes processes "may be the intention of especially designed activities to influence the social setting (intended impacts) or may unintentionally result from these activities" [54]. Vanclay [54] also argues that "many of the variables typically measured in social impact assessment studies are not in themselves impacts, but rather represent the measurable outcomes of social change processes, which may or may not cause impacts depending on the situation".
- Vanclay [54] proposes a list of social impacts covering different dimensions (individual, family, household unit, community, and society) and specificities (corporeal, perceptual, and/or emotional). The conceptualization of the impacts was divided into seven categories (but according to the author it is possible to group them in other ways):

- Health and social well-being: This category is based on health impact assessment (HIA) [69]. Vanclay stresses "while HIA professionals have a wide range of health indicators, they consider that the dimensions listed are the ones likely to be important from a social perspective" [54].
- Quality of the living environment (liveability): This category includes impacts related to the physical environment, like exposure to dust, noise, artificial light, odours, and other similar issues. It also includes how people feel about their environments, that is, the recreational opportunities and the aesthetic quality of their surroundings.
- Economic and material well-being (both on individuals and on communities): In developed countries, employment opportunities, income, and real estate are apparent impact variables, while in less-industrialized countries the workload, for instance, is more important.
- Cultural: This category "includes all impacts (changes) on the culture or cultures in an affected region, including loss of language, loss of cultural heritage, or a change in the integrity of a culture (the ability of the culture to persist)" [54].
- Family and community: This category "includes impacts related to the family, social networks, and the community" [54]. Changes in family structures and communities are examples of impacts included in this category.
- Institutional, legal, political, and equity: In this category, the workload and the viability of government or official agencies is included. Also, it considers alterations resulting from the implementation of projects with great commercial interest, which can create pressure on institutions and governments, violating the human rights of individuals.
- Gender relations: Since "women tend to bear the largest and most direct social impacts" [54], this category encapsulates this social impact.

Despite Vanclay [54] proposing a list of possible social impacts for each category, he warns against its use as a checklist, since it does not encourage analytical thinking about the impact-causing mechanism. Furthermore, he adds that any listing of impacts is context dependent, so researchers must select what impacts should be included and how they should be described, bearing in mind that the level of detail is crucial.

In the case of the social impacts of AM technology, existing studies are scarce. In the face of such arguments, this research proposes a list of the social impacts of AM technology, based on the definition of social impact given by Vanclay [54].

2.3. Social Impacts of Additive Manufacturing

Due to the lack of social impact repositories applied to AM technology, a number of Vanclay's [54] categories, and their respective list of social impacts, were considered as the foundation for this study. In particular, four categories of social impacts were considered relevant: (1) Health and social well-being, (2) institutional, legal, political, and equity, (3) quality of the living environment (Liveability), and (4) economic and material well-being. Since Vanclay's list is intended for any topic and it does not focus on AM, the four categories were selected considering the pieces of evidence found in the AM literature, as well as a recent study [70]. The purpose of the study was to map specific keywords, or "pointers", for social impacts of AM technology. The computer-aided content analysis applied in the study allowed the authors to disclose many significant "pointers", in which the words "family" or "gender", for instance, never appeared as an output [70].

Table 1 was compiled using Vanclay's social impacts list and was completed with the social impacts identified in the AM literature. It provides an overview of the potential AM social impacts and is not an extensive or absolute list of social impacts. For each impact, a description is given according to Vanclay [54] or other authors. In some cases, the impact was defined by the authors of this paper, which is denoted where relevant in the right-most column.

Table 1. The social impacts of AM.

Category	Social Impact	Description	References
Health and Social Well-being	Perceived health.	Impacts on health.	[54]
		Health, safety, and social benefits at work.	[16]
	Mental health and subjective well-being.	Feelings of stress, anxiety, apathy, depression, etc.	[54]
	Change of aspirations for the future for self and children.	Expectations about what will come (more jobs, more economic growth, etc.).	[54]
	Dissatisfaction due to the failure of promised benefits.	Expectations, disappointment, resentment, or dissatisfaction.	[54]
Quality of the Living Environment (Liveability)	Perceived quality of living environment.	Work: Regarding dust, noise, risk, dour, vibration, blasting, artificial light, and safety.	[54]
		Life expectancy and quality of life. Waste management.	[11,15,17]
	Leisure and recreation opportunities and facilities.	Recreational and leisure opportunities.	Proposed by the authors.
	Actual crime and violence.	Crime and violence changes.	[54]
		Printing weapons for illegal purposes.	[28,47]
Economic and Material Well-Being	Workload.	The amount of work that is required to live reasonably.	[54]
	Access to public goods and services.	Facilities for accessing public goods and services.	Proposed by the authors.
		Biological models, medical implants, organs, and prosthetics can be manufactured according to patient's needs.	[21,22]
	Economic prosperity and resilience.	Economic affluence of a community and the extent of diversity of economic opportunities.	[54]
	Occupational status and type of employment.	Professional situation and type of employment.	Proposed by the authors.
		Labour intensity, employment schemes, types of work, work conditions, working hours, working places, etc. Changes in knowledge and skills.	[16,17,44]
	Level of unemployment in the community.	Underutilization of human capital.	[54]
	Loss of employment options.	Loss of employment resulting from new technology.	Proposed by the authors.
		Job and work safety losses.	[15]
	Economic dependence or vulnerability.	Individual or household control over economic activities.	[54]
	Disruption of the local economy.	Disappearance of local economic systems and structures.	[54]
		Capacity to enable indigenous entrepreneurs to design and build more advanced products tailored for local markets.	[71]
Institutional, Legal, Political, and Equity	Workload and viability of government and formal agencies.	Implementation of projects with great commercial interest can create pressure on the institutions and governments.	[54]
		Patents and copyrights could change significantly.	[72,73]

3. Research Methodology

Given the exploratory nature of this research and the need to build theory in this developing research area, a multiple case study methodology was selected for this study [74,75]. Four organizations that use AM manufacturing processes were selected for exploring the proposed research questions. Factors of convenience (namely ease of access) and proximity were important reasons for the selection cases. All of the selected organizations are located in Portugal (Lisbon and the Tagus River Valley).

To collect data related to the social impacts of AM, an interview protocol was designed considering the social impacts identified in Table 1. The main objective was to collect the interviewees' perceptions about factors of AM technology that can lead to changes and the effect of those factors in terms of their social impact (which can be positive, negative, null, or mixed). The interview was comprised of semi-structured questions, as well as questions to encourage interviewees to share their opinions and experiences. Each interview ended with an open question on the "most experienced or perceived impact(s)", so there was a chance to apprehend other items neglected in Table 1. To test the interview protocol, a pilot-run was carried out with two young entrepreneurs who were well-acquainted with AM technology. After that, the interview protocol was refined.

The data were collected over two weeks, through four semi-structured interviews, conducted with the senior managers of the organizations. Each interview lasted about 1.5 h and was electronically recorded. The quality of the data collected was ensured by two means: (1) In addition to the use of a digital tape-recorder, all interviews were conducted by two researchers, and (2) all statements/results were transcribed into a summary text and sent out to the respective interviewee for his/her validation of contents, both in terms of the completeness and interpretation. This direct approach allowed the collection of data on the social impacts originating from AM and the perceived impact direction. The relevant results are compiled in Tables 4 and 5, which are presented later in this paper.

4. Case Study Results and Analysis

4.1. Social Impacts of Additive Manufacturing

The four organizations comprising the multiple case study (Table 2):

- Organization A: 3D Life is a brand (and a business unit) within the company Let's Copy Ltd., a Portuguese small and medium-sized enterprise—(SME). It provides services such as 3D scanning, digitalization, printing, modelling, and short run productions. This company uses ceramic, plastic (PLA), and resin printers, and they work together with other partners using other technologies such as metal printing. The organization mostly makes prototypes for validation and ergonomic studies and creates small print runs for large companies.
- Organization B: Blocks Technology is a Portuguese start-up for the design and manufacture of 3D printers. Initially, the company developed prototypes for other companies, but currently, it designs and manufactures their own 3D printers and sells filaments and maintenance services.
- Organization C: 3D Factory is also a brand (and a business unit) within the company Emerging Objects (a Portuguese SME), which provides services for 3D scanning, digitization, printing, and modelling (technical and prototyping, architectural models/applications, and equipment). Its main products are "end products", (i.e., objects, prototypes of products, and parts). The company also provides complementary services such as modelling, design, and printing for projects. Its primary clients are educational, musicological, and creative services.
- Organization D: MILL—Makers In Little Lisbon is a community of practice. This collective focuses on collaborative work and knowledge sharing. The interviewee of this practice community has the peculiarity of having introduced in Portugal, in 2009, the first 3D printer from the MakerBot Company. This expert has in-depth knowledge of the history of 3D manufacturing in the world and has participated in the process of the expansion of desktop 3D printers.

Table 2. Summary of the organizations under study.

Name	3DLife (A)	Blocks Technology (B)	3D Factory (C)	Mill (D)
Type	Brand.	Start-up.	Brand.	Collaborative community.
Main Products/Services	3D scanning, digitalization, printing, modelling, and short-run production.	Design and manufacture of 3D printers, and maintenance services.	3D scanning, digitalization, printing, modelling, and short-run production.	Knowledge sharing.
Main Customers	End users and manufacturing companies.	Companies.	Educational, museological, and creative services.	Not applicable.
Additive Technology	Ceramic, plastic (PLA), and resin printers.	PLA printers.	PLA, Acrylonitrile Butadiene Styrene (ABS), laser, and resin printers.	PLA printers.

Table 2 characterizes the four organizations. In addition to the table contents, it is noteworthy that all of them are under 5 years old, had a business volume in 2017 of up to 100,000 EUR, and have fewer than 10 employees, all of which have at least a bachelor's and/or licentiate's degree.

4.2. Social Impacts of Additive Manufacturing

The data collected were analysed using a colour coding scheme (Table 3), indicating the agreement between the four respondents on the "direction" of each impact, which was either positive, negative, null, or mixed.

Table 3. Level of agreement between interviewees.

	Colour Code
(dark green)	All Positive (*the 4 respondents agree on a positive impact*)
(light green)	Positive + Null
(yellow)	Positive + Negative and/or Mixed and/or Null (i.e., *undefined*)
(orange)	Negative + Null
(red)	All Negative (*the 4 respondents agree on a negative impact*)
(grey)	All Null (*the 4 respondents agree – no impact*)

Tables 4 and 5 present a list of factors of AM technology that can lead to changes. In addition, they contain a list of social impacts (i.e., the effect of the change). The objective is to show the cause-effect relationship between factors ("causes") and effects ("impacts"). The "causes" (the mechanisms that can generate changes) are the specific characteristics of the AM technology which may help to explain the perceived "impact". The next sub-sections provide the analysis of main results.

4.2.1. Vanclay's Theoretical Framework

Table 4 shows the interviewees' perceptions of the social impacts of AM related to health and safety, mental health, and well-being, as well as expectations for the future.

The first factor, "occupational disease situations", represents the exposure to health risk factors such as a thermal environment, noise, and vibration (i.e., physical risks of the work environment). All the interviewees stated that AM technology has a positive impact on worker health and safety. According to them, this risk almost disappears, because the equipment is noiseless, the machines can run on their own (higher autonomy) and the workers are "removed" from the process, as compared with conventional technologies in which there is a more constant and closer man-machine contact. In fact, some of the respondents emphasized that in many small companies, the factory environment disappears, and everything is similar to an open-space layout, typical of service companies, where the manufacturing zones coexist with administrative workspaces. These results are aligned with the literature [11,15,16], since is frequently referred to as a positive social impact.

Table 4. Cross case analysis of the categories of health and social well-being, quality of life, and institutional and legal level.

Social Impact Categories / Questions	AM Changes Can AM technology lead to changes in the following factors?	Answer: No	Answer: Does Not Know	Answer: Yes	AM Social Impacts What is your perception of the factors' Effect on:	Answer: Positive	Answer: Negative	Answer: Null	Answer: Mixed	Final Assessment
Health and Social Well-Being	Occupational disease situations, e.g., thermal environment, noise, or vibration.			ABCD	Health and Safety	ABCD				
	Situations of accidents at work, e.g., dangerous machines, burns, electric shocks, or cuts.	ABCD						ABCD		
	Number of hours of mental and/or physical work, e.g., time spent paying attention to the different aspects of the production process.	ABCD						ABCD		
	Situations of particular risks, e.g., inhalation of particles during the production or finishing.			ABCD			ABCD			
	Level of stress and/or anxiety at work, e.g., watchfulness stress of the productive process.	ABC		D	Mental Health and Well-Being			ABC	D	
	Feelings of social valorisation/recognition of professional status. Internal or external valorisation.			ABCD	Expectations for your Future	ABCD				
Quality of Life	New recreational and leisure activities, e.g., hobbies or the manufacture of personal objects.			ABCD	Perception of Leisure and Recreation	ABCD				
	Level of crime and violence, e.g., ease of making weapons or bombs.	BCD	A		Perception of Real Crime and Violence			BCD		
Institutional and Legal Level	Protection of patent rights, e.g., open source files.		BC	AD	Legal Rights	D	A			

Table 5. Cross case analysis for the category of economic and material wellbeing.

Social Impact Categories	Questions AM Changes Can AM technology lead to changes in the following factors?	Answer No	Answer Does Not Know	Answer Yes	AM Social Impacts What is your perception of the factor effect on:	Answer Positive	Answer Negative	Answer Null	Answer Mixed	Final Assessment
Economic and Material Wellbeing	Adaptation of products' characteristics to the needs/expectations of the community, e.g., making traditional objects/artefacts.			ABCD	Disruption with the Local Economy	ABCD				
	Creation/disappearance of small local businesses, e.g., local production models.			ABCD		AB			CD	
	Customisation/personalisation and creating personalized products.			ABCD	Economic Prosperity	ABCD				
	Reward systems, e.g., compensation by objectives, to guarantee efficiency in production.	BCD		A		A		BCD		
	Development of new skills that can be used in new businesses, e.g., digital entrepreneurship.			ABCD		ACD			B	
	Creation/disappearance of jobs, e.g., work at home or new jobs.			ABCD	Level of Employment in the Community				ABCD	
	Educational curricula, e.g., the teaching of AM technology in technical-vocational education.			ABCD	Professional Status and Employment Type	ABCD				
	Need to participate in training and professional requalification, e.g., training in new software/hardware.			ABCD		ABCD				
	Function analysis (roles), e.g., new tasks within the product design/production processes.	D		ABC		ABC		D		
	Work organization, e.g., changes in workspaces and layouts		C	ABD		ABD				
	More flexible work schedules, e.g., adapting human resource needs to the production cycle.	AB		CD		CD		AB		
	Performance assessment system, e.g., introducing management by objectives.	BCD		A		A		BCD		
	Responsibility for the tasks performed, e.g., production errors are costly.	CD		AB		AB		CD		
	Need of teamwork. Need to join different skills.	D		ABC		C		D	AB	
	Need to develop new skills, e.g., the use of the new equipment and software			ABCD		ACD			B	
	New work schemes, e.g., remote work/work at home.	A		BCD		CD		A	B	
	Precarious contracts, e.g., the provision of services and fixed-term contracts based on productive objectives	D		ABC		A		D	BC	
	Turnover, because of the high demand for specialists in AM technology.	A		BCD		D		A	BC	
	Resistance to organizational and technological change, e.g., difficulties in implementing new work schemes or changing roles.	BCD		A			A	BCD		

Likewise, in the factor "feelings of social valorisation/recognition of professional status", all the interviewees agreed that the impact on "expectation for your future" was positive. They justified this, claiming AM technology is seen as something new, revolutionary, modern, and appealing, allowing varied and creative work.

In contrast, for the factor "situations of particular risks", the impact on "health and safety" is unanimously negative, because there is an added risk on both occupational health and worker safety. This is explained by the increased use of a wide range of raw materials, namely thermoplastics and composites that release toxic particles and fumes, increasing the risk for health, either through direct contact with the skin or inhalation [11,12,15].

Regarding the impacts on "health and safety" caused by "situations of accidents at work" and the "number of hours of mental, and/or physical work", all interviewees agreed that the effect was null, since the machines are safe, do much of the work without human intervention, and there is already enough know-how on this technology.

Similarly, the impacts on "mental health and well-being", caused by the "level of stress, and/or anxiety at work", received a null classification from three interviewees. The exception was the representative of the collaborative community. His justification for the mixed effect caused by "level of stress, and/or anxiety at work", concerning impact, was that some AM applications are still quite slow, and this could increase stress levels when there are short deadlines to meet.

4.2.2. Impacts on Quality of Life

This category includes aspects such as recreational and leisure activities and the perception regarding the impact of AM on crime and violence. All the interviewees said that this technology allows countless leisure activities, valuing the concept of do it yourself (DIY) and allowing the development of creativity, enabling the production of objects for cultural expression and educational activities. This corroborates other findings in the literature review, e.g., [3].

The possibility of using AM technology to reproduce replicas from museum objects and develop "3D museums" was also mentioned, resulting in opportunities of social inclusion (e.g., people with visual impairment).

About the "level of crime and violence", one respondent (A) stated that he did not know whether there was an impact. However, the other three respondents stated that there will be no effects, since it is easier to manufacture weapons or bombs by other means. In fact, regarding this question, the three respondents were peremptory in affirming that AM does not increase the risk of violence. These findings are contrary to what is advocated by some authors [28,45], who believe that AM technology can increase insecurity and violence.

4.2.3. Impacts on Institutional and Legal Level

The perceptions of the interviewees regarding their legal rights were divergent. Even though organizations B and C claim to be unaware of the potential impacts, organizations A and D believe that there is an impact: Organization A believes that the protection of patent rights is a factor with negative impact, since AM creates the possibility of numerous copies, compromising patent security. For organization D, this is a factor with a positive impact, since working on open source models is important because the information is entirely available to all. This result is in line with the literature analysed, which considers that property rights and policies are not clear [17,30,31].

4.2.4. Impacts on Economic and Material Well-Being

The main category, "economic and material well-being" (Table 5), includes issues related to disruption with the local economy, economic prosperity, the level of employment in the community, and professional status or type of employment. Since this category includes 19 factors, it was considered helpful to show a relative distribution for mapping both the direction of the impacts and the level of agreement, as can be observed in Figure 2.

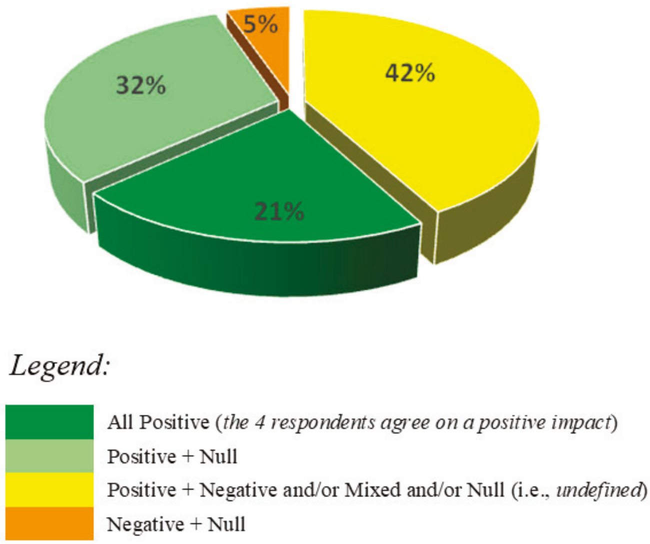

Figure 2. Impacts on economic and material well-being, showing the direction and the level of agreement.

It can be established from the results that the opinion of respondents on the impacts of the category "economic and material well-being" were frequently coincident (Table 5) and mostly positive (Figure 1), since more than half the items are labelled in the colour green (21% + 32%).

Regarding the potential effect of "disruption with the local economy", all interviewees agreed that the factor "adaptation of products' characteristics to the needs/expectations of the community" has a positive impact, because the use of the AM technology allows customization and better management of stocks, since these are manufactured upon request. This in line with the literature [25,33].

Furthermore, the changes in the "creation/disappearance of small local businesses" can have both positive and mixed impacts on the "disruption with the local economy". For a couple of respondents, there was no problem (perceived as positive impact) because they believed that new small AM businesses can coexist with traditional businesses. The other two respondents were unsure and considered "mixed" impacts, since there is still some chance that a few traditional businesses can disappear.

With regards to perceived effects on "economic prosperity", the respondents were almost unanimous in considering that changes in "customization/personalization" and "new skills that can be used in new businesses" have positive impacts. AM allows acquiring new skills that can be used to develop new business. However, the interviewee from organization B considered that the impacts are mixed, since the development of new skills is positive, but, conversely, it can also create unemployment and poverty due to the low qualification of some workers. Customization was pointed out by all interviewees as a significant change, since it allows the ability to quickly answer customer expectations. This confirms the relationship between AM and customization that is advocated in the literature [5,12,15,47,76]. Most respondents believe that there will be no changes in the "rewards system". However, one of the interviewees pointed out that AM processes facilitate management by objectives.

The effect on the "level of employment in the community" received a mixed classification by all interviewees when assessing the change "creation/disappearance of jobs", since this technology promotes both the creation of some jobs and the disappearance of others.

Within the impact on "professional status and employment type", a wider variety of factors were assessed. All the interviewees were unanimous in considering that "educational curricula" and the "need to participate in training and professional requalification" have a positive impact in professional status and employment. Changes in education and training were referred to by the interviewees as one of the areas which can benefit most from the introduction of qualifications in the domain of AM technology. One of the interviewees mentioned that recruitment processes in engineering areas are already valuing knowledge of the use of 3D technology. The importance of developing new skills and competencies for AM is also mentioned in the literature as a positive effect [11,17,36,37].

The trend to use "open office" schemes supports the perceptions of the interviewees that "function analysis" and "work organization" have a positive impact on "professional status and employment type".

Two of the interviewees considered that "more flexible work schedules" has a positive impact, since several porTable 3D machines can be easily used anywhere (i.e., the home, office, events, etc.). Two others considered that there will be no impact concerning this factor.

"Performance assessment system" was considered without impact (impact null) or with positive impact (A), because these systems become very objective, allowing the unequivocally verification if the employee has complied with the procedures defined by the company within the stipulated period. All these factors were considered positive by respondent A. This last explanation is also the reason why two interviewees considered that "responsibility for the tasks performed" has a positive impact.

Regarding the effect of "need of teamwork", there were different perspectives. It is important (and beneficial) to work as a team, because the various stages of production must be well synchronized. If an individual makes an error (e.g., programming the machine incorrectly) it can jeopardize the entire process.

According to three interviewees, the factor "need to develop new skills" has a perceived positive impact, because the evolution of this technology forces employees to be up to date/keep up with the development of technology.

"New work scheme" changes were perceived as generators of positive and mixed impacts on "professional status and employment type", since these schemes increasingly allow remote work systems, but at the same time, there may be negative impacts that result from an excess of employees who can work from home or other locations. Remote work allows higher professional flexibility, but it can also "isolate" individuals from their workplace and organization, creating risks inherent to "work alone" situations, typically psychosocial risks.

The factors "precarious contracts" and (personnel) "turnover" seem to be related. Both are likely to increase because there is a shortage of AM specialists. At least two of the interviewees (B and C) believe that there are both positive and negative effects. On the one hand, the freelance qualified workers are encouraged because they can easily change from one company to another, creating new opportunities for "self-employment". On the other hand, this also means precarious jobs, which are justified by the typology of production management "by project".

Finally, the interviewees' perceptions of the effects of "resistance to organizational and technological change" on "professional status and employment Type" was that it has almost no impact. However, one of the interviewees considered that the impact is negative, since there is some resistance to organizational and technological change.

4.2.5. Emerging Social Impacts and Factors

Each respondent was asked to pinpoint the "most" important AM social impact(s) and/or factors causing them. Several items emerged as follows:

- Customization: Each person can replicate parts of objects that they need, and/or create/print new parts.
- Decreased consumerism: Repairing becomes easier.
- Increased durability of products/equipment: Due to maintenance/repair of equipment with customized parts, when printed in 3D, the durability of equipment and parts may increase.
- Reduction of stocks: The use of AM technology decreases the need to maintain stocks.
- Environmental problems: It is felt necessary to identify, systematically, different materials by type and to create mechanisms for their classification, separation, and recycling.

- Quality of life: AM technology used for medical purposes enables the production of prostheses, organs, teeth, etc., improving people's quality of life.
- Employment: AM technology can increase unemployment, especially for many unqualified people, despite the counter-effect of promoting a few qualified ones.
- Education: AM technology can be used to improve learning processes.
- Cultural: AM technology can be applied in museums and thematic cultural events, through the rapid reproduction of 3D miniatures (e.g., iconic statues and monuments, dinosaurs in thematic parks, etc.).
- Social inclusion: AM technology can contribute to social inclusion, for example by allowing blind people to experience museums more realistically.

5. Conclusions

This paper presents an endeavour to determine the social impacts of AM and the respective causes of said impacts. An exploratory multiple case study, comprised of four organizations, was developed considering three research questions.

The first research question (RQ1) aimed at identifying "causes", i.e., the main factors originated by the use of AM technology in a productive context that could cause any type of social impact. The research underlined a set of 28 fundamental factors that may create social impacts within the health and social well-being of people (including work conditions), quality of life, legal issues, and wealth generation. Of these, 12 specific factors were pinpointed unanimously by all four organizations as creating changes (column "yes"), namely disease situations, situations of particular risks, feelings of social valorisation/recognition of professional status, new recreational and leisure activities, adaptation of product characteristics to the needs/expectations of the community, creation/disappearance of small local businesses, customisation/personalisation, development of mew Skills that can be used in new businesses, creation/disappearance of jobs, educational curricula, need to participate in training and professional requalification, and need to develop new skills. By contrast, at least three factors were likely to have no social impact (null impact): Situations of accidents at work, number of hours of mental and/or physical work, and level of crime and violence. The latter is surprising, since it contradicts other findings in the AM literature [28,45]. However, a list of undefined or fuzzy factors also emerged. The case with the protection of patent rights is one that raises doubts and needs further investigation.

The second research question (RQ2) intended to identify the "effects", i.e., the types of AM social impacts. Following Vanclay's social impacts definition [19], this paper proposes 10 social impacts related to AM, which are organized into four categories and respective subcategories: (1) Health and social well-being, with the subcategories of health and safety, mental health and well-being, and expectations for the future; (2) quality of life, with the subcategories of perception of leisure and recreation, and perception of real crime and violence; (3) institutional and legal level, with the subcategory of legal rights; and (4) economic and material well-being, with the subcategory of disruption with the local economy, economic prosperity, level of employment in the community, and professional status and employment type. The case study results allowed the confirmation of this set of social impacts and unveiled another two, cultural impacts and social inclusion.

The third research question (RQ3) helped explain the cause-effect relationships between AM factors and their social impacts. To answer this question, it was assessed if the impacts were perceived as positive, negative, null, or mixed. Apparently, AM technology has many positive impacts, such as improved health and safety due to a reduction of occupational diseases caused by physical hazard, higher expectations for the future, derived from feelings of social valorisation/recognition of professional status, new opportunities for leisure and recreation, given the chance to develop new hobbies and other recreational activities, disruption within the local economy in a positive direction, with the adaptation of products to the needs of the community, economic prosperity, originating from the increased demand for product customization, and finally, increased professional status and innovative employment types, instigated by new educational curricula and training and qualification schemes.

However, one negative impact of AM technology was identified by all; the possibility to reduce worker health and safety due to particular risks, namely exposure to dangerous substances.

The main limitations of the current study arise from three methodological aspects. Firstly, the use of a case study methodology. The results can be influenced by contextual factors, such as the size of the organizations in the sample, and/or social, cultural, technological, political, economic, and ecological factors. Directly associated with this issue, it should be highlighted that the cases selected were restricted to micro-enterprises. This was due to geographical proximity and to keep a manageable (short) number of homogeneous cases. A subsequent and much more extended study is currently being carried out, including a survey with a large number of enterprises of all sizes and from a variety of activity sectors. Finally, it should also be acknowledged that, in the future, all seven categories of Vanclay's list of impacts should be explored with respect to AM technology.

All in all, the present study, just like a few of its predecessors, appears to corroborate a multitude of positive social impacts for AM technology. However, this somewhat optimistic vision should be tackled with caution and more research work, since AM is still in its early days and other less interesting impacts may still be unknown. Finally, key research directions in the AM technology field can be summarized as follows:

- Developing a more comprehensive study on AM social impacts, considering a larger sample and replicating the study in several countries.
- Verifying if the use of different raw materials and equipment can lead to different social impacts.
- Developing methodologies to quantify (including formal indicators) the relevance of AM technology's social impacts.
- Creating an open database of possible AM social impacts, specifying the differences between the varied raw materials and equipment involved.

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Considering Product Life Cycle Cost Purchasing Strategy for Solving Vendor Selection Problems

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Abstract: The framework of product life cycle (PLC) cost analysis is one of the most important evaluation tools for a contemporary high-tech company in an increasingly competitive market environment. The PLC-purchasing strategy provides the framework for a procurement plan and examines the sourcing strategy of a firm. The marketing literature emphasizes that ongoing technological change and shortened life cycles are important elements in commercial organizations. From a strategic viewpoint, the vendor has an important position between supplier, buyer and manufacturer. The buyer seeks to procure the products from a set of vendors to take advantage of economies of scale and to exploit opportunities for strategic relationships. However, previous studies have seldom considered vendor selection (VS) based on PLC cost (VSPLCC) analysis. The purpose of this paper is to solve the VSPLCC problems considering the situation of a single buyer–multiple supplier. For this issue, a new VSPLCC procurement model and solution procedure are derived in this paper to minimize net cost, rejection rate, late delivery and PLC cost subject to vendor capacities and budget constraints. Moreover, a real case in Taiwan is provided to show how to solve the VSPLCC procurement problem.

Keywords: vendor selection; product life cycle; multi-objective linear programming; multi-choice goal programming

1. Introduction

Modern businesses face an increasingly competitive market environment, in which companies need to shorten product life cycle (PLC) to bring their good products to market quickly, and thereby increase their competitive advantages. In particular, the PLC of electronic products has become shorter to support the timing of marketing [1]. A significant challenge faced by the vendor–buyer supply chain (SC) is how to deal with the arrangement of the vendor's uncertain lead time and the buyer's random demand over the selling season [2]. Accurately determining timing for purchasing is an important issue for procurement plans. The PLC-purchasing strategy (PS) offers a framework for procurement plans and examines the sourcing strategy of a firm [3,4]. PLC is a descriptive framework that classifies the development of product-markets into four stages: Introduction, growth, maturity, and decline. In the introduction stage, there are few competitors in the market. This provides innovators with a chance to use a price-skimming strategy to recoup their product development costs and encourage knowledge of the new product. In the growth stage, overall market sales increase radically, attracting many new market entrants. The decline stage is entered when overall market sales begin to fall. During this stage products are withdrawn from the market and firms reduce their marketing expenditures to cut costs [5]. It can be seen that using the framework of PLC can act as a guideline to aid purchasing managers in fitting the performance of their ever-expanding duties and tasks for the optimal profit of the company. Purchasing planners have known that they want to achieve this desired elasticity by fitting procurement actions to each PLC phase. The emphasis on this procurement planning is on the timing of the changes in purchasing activities to create the best utilization of company resources [6]. Schematically, the PLC can be approximated by a bell-shaped curve that is divided into several stages. The PLC is typically depicted as a unit sales curve of a product category over time [7–16]. Another important issue faced by firms is the vendor selection (**VS**) problem. Supply professionals must balance their firm's quality and delivery policies with the cost saving and flexibility profit offered by vendors, so a vendor's product manufacturing skills are attractive early on the relationship but efficiency dictates in later stages [7]. The purchasing firm's preferences or weights associated with various vendor attributes may vary during different stages of the PLC. The concept of PLC cost (**PLCC**) originates from the US Department of Defense and is focused on a product's entire value chain from a cost perspective since the development phase of a product's life, through design, manufacturing, marketing/distribution and finally customer services [8]. Elmark and Anatoly (2006) indicated that the PLCC is the total cost of acquiring and utilizing a system over its complete life span [10]. Vasconcellos and Yoshimura (1999) proposed a breakdown structure to identify the main activities for the active life cycle of automated systems [11]. Spickova and Myskova (2015) proposed activity based costing, target costing and PLC techniques for optimal costs management [12]. Sheikhalishahi and Torabi (2014) proposed a VS model considering PLCC analysis for manufacturers to deal with different vendors offering replaceable/spare parts [13]. Narasimhan and Mahapatra (2006) developed a multi-objective decision model that incorporates a buyer's PLC-oriented relative preferences regarding multiple procurement criteria for a portfolio of products [3]. Life cycle costing is concerned with optimizing the total costs in the long run, which consider the trade-offs between different cost elements during the life stages of a product [17]. In brief, the PLCC methodology aims to assist the producer to forecast and manage costs of a product during its life cycle. PLCC is a good technique used to assess the performance of a PLC. It can evaluate the total cost incurred in a PLC and assist managers in making decisions in all stages [9]. Their research aims to obtain a comprehensive estimation of the total costs of alternative products or activities in the long run. It is usually possible to affect the future costs beforehand by either planning the use of an asset or by improving the product or asset itself [18]. Previous studies, however, have seldom examined the VSPLCC procurement problem in the situation of single buyer–multiple supplier. The contribution of the study is to consider a VSPLCC problem with a single-buyer multiple-supplier procurement problem. We integrate VS and PLCC (VSPLCC) procurement planning into a model for enterprise to reduce their purchasing cost. Based on the literature reviews and discussions with experts in this field, we obtained important criteria, including price, transportation cost, quality, quality certification, lead time, necessary buffer stock, goodwill, PLC cost, vendor reliability, and vendor-area-specific experience in the VSPLCC problem of real case example. In addition, we would like to maximize the benefit of the procurement process and must continue to reduce purchasing costs as well as aim to achieve minimal costs to obtain the maximum benefit. To help purchasing managers effectively perform and coordinate these responsibilities with their jobs, we need to reconceptualize their role for procurement [14,15]. A new VSPLCC procurement model is then proposed to solve the problem of real case example procurement problem and is presented based on the modified dataset of the auto parts manufacturers' example, and a numerical example is adopted from a light-emitting diode company in Taiwan. Our study considers the following goals: For more realistic applications, net cost minimization, rejection rate minimization, and late delivery minimization, minimization of PLCC, and vendor capacities and budget constraints. Moreover, multi-objective linear programming (MOLP) and multi-choice goal programming (MCGP) approaches are integrated to solve this VSPLCC procurement problem.

The paper is organized as follows. We review the literature regarding the quantitative methods for the VS decision in Section 1. Section 2 presents the formulations and solutions to the VSPLCC procurement problem using both MOLP and MCGP approaches. In Section 3, the solution procedures of the two approaches for VSPLCC procurement problem are presented based on the modified dataset of the auto parts manufacturers' example and a numerical example is adopted from a light-emitting diode company in Taiwan [19]. In Section 4 Solution results of MOLP and MCGP are provided. Conclusions regarding the managerial implications and limitations solving the VSPLCC procurement problem in the four stages of the PLC with MOLP and MCGP approaches are addressed in Section 5.

2. The VSPLCC Procurement Approaches

2.1. Linear Programming Technique

Linear programming (LP) is a powerful mathematical technique which can be used to solve PLC problem. Azapagic and Clift (1998) applied LP to assess the environmental performance of a product system [20]. Dowlatshahi (2001) developed a conceptual framework to tactically consider PLC costs [21]. Zimmermann (1978) showed that a problem with fuzzy goals and constraints can be reformulated as conventional LP problem [22]. Ghodsypour and O'Brien (1998) utilized AHP and LP to develop a decision support system for solving VS problems [23]. Kumar et al. (2004) used fuzzy GP to address the effects of information uncertainty on the VS problems [24]. Amid et al. (2006) developed a fuzzy multi-objective LP model to overcome the VS problem with vague information [25]. In addition, Kagnicioglu (2006) first compared two fuzzy multi-objective methods for VS problems [26]. Chang (2007, 2008) proposed the MCGP method which allows one goal mapping multiple aspiration levels to find the best achievement levels for multiple objective decision making (**MODM**) problems [27,28]. Accordingly, in order to improve the quality of decision making for solving the VSPLCC procurement problem, we integrate AHP and MCGP methods, wherein both qualitative and quantitative issues are considered for more realistic VSPLCC applications. The AHP-MCGP method is also used to aid decision makers (DMs) in obtaining appropriate weights and solutions for the VSPLCC problem. The proposed VSPLCC procurement model can be easily used to select an appropriate vendor from a number of potential alternatives. The framework adopted for this study is shown in Figure 1.

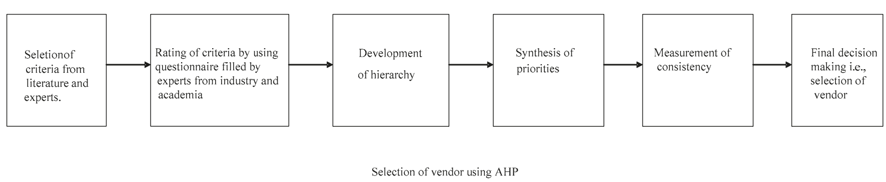

Figure 1. Framework of the study.

The formulation of the VSPLCC procurement model requires the following assumptions, indices, decision variables and parameters.

2.2. Fuzzy Multi-Objective Models for the VSPLCC Procurement

VSPLCC Procurement Problem

(i) One item is purchased from each vendor.
(ii) Quantity discounts are not considered.
(iii) No shortage of the item is allowed for any of the vendors.
(iv) The lead time and demand for the item are constant and known with certainty.

The sets of indices, parameters, and decision variables for the VSPLCC model are listed in Table 1.

Table 1. Nomenclature [fuzzy parameters are shown with a tilde (~)].

i	Index for vendor, for all $i = 1, 2, ..., n$
j	Index for objectives, for all $j = 1, 2, ..., J$
k	Index for constraints, for all $k = 1, 2, ..., K$
t	index objectives and constraints for all at four PLC stages $t = 1, 2, 3, 4$
Decision Variable	
X_{it}	Ordered quantity given to the vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
Parameters	
$\widetilde{D}_t$	Aggregate demand for the item over a fixed planning period, $t = 1, 2, 3, 4$ index for all at four PLC stages
n	Number of vendors competing for selection
p_{it}	Price of a unit item of ordered quantity x_i for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
Q_{it}	Percentage of the rejected units delivered for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
L_{it}	Percentage of the units delivered late for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
C_{it}	Product life cycle cost of ordered for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
$\widetilde{U}_{it}$	Upper limit of the quantity available for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
r_{it}	Vendor rating value for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
P_{it}	The total purchasing value that a vendor can have, $t = 1, 2, 3, 4$ index for all at four PLC stages
f_{it}	Vendor quota flexibility for vendor i, $t = 1, 2, 3, 4$ index for all at four PLC stages
F_{it}	The value of flexibility in supply quota that a vendor should have, $t = 1, 2, 3, 4$ index for all at four PLC stages
B_{it}	Budget constraints allocated to each vendor, $t = 1, 2, 3, 4$ index for all at four PLC stages

2.3. VSPLCC Procurement Model

The multi-objective VSPLCC procurement problem with four fuzzy objectives and some constraints are as follows:

$$\text{Min } Z_{1t} \cong \sum_{i=1}^{n} \sum_{t=4}^{4} P_{it} X_{it} \text{ the total net cost} \quad (1)$$

$$\text{Min } Z_{2t} \cong \sum_{i=1}^{n} \sum_{t=1}^{4} Q_{it} X_{it} \text{ the reject items for vendor } i \quad (2)$$

$$\text{Min } Z_{3t} \cong \sum_{i=1}^{n} \sum_{t=1}^{4} L_{it} X_{it} \text{ the late delivered items for vendor } i \quad (3)$$

$$\text{Min } Z_{4t} \cong \sum_{i=1}^{n} \sum_{t=1}^{4} C_{it} X_{it} \text{ the product life cycle } \cos\text{t for vendor } i \quad (4)$$

The following constraints are given for the VSPLCC procurement problem:

$$\sum_{i=1}^{n} \sum_{t=1}^{4} X_{it} \geq \widetilde{D}_t \text{ (aggregate demand constraint)} \quad (5)$$

$$X_{it} \leq \widetilde{U}_{it}\ i = 1, 2, \ldots, n, = 1, 2, 3, 4, \text{ (capacity constraint)} \quad (6)$$

$$\sum_{i=1}^{n} \sum_{t=1}^{4} r_{it}(X_{it}) \geq p_{it};\ t = 1, 2, 3, 4, \text{ (total items purchasing constraint)} \quad (7)$$

$$\sum_{i=1}^{n}\sum_{t=1}^{4} f_{it}(X_{it}) \leq F_{it};\ t = 1, 2, 3, 4,\ (\text{quota constraint}) \tag{8}$$

$$P_{it}X_{it} \leq B_{it};\ i = 1, 2, \ldots, n,\ t = 1, 2, 3, 4,\ (\text{budget constraint}) \tag{9}$$

$$X_{it} \geq 0,\ i = 1, 2, \ldots, n,\ t = 1, 2, 3, 4.\ (\text{non}-\text{negativity constraint}) \tag{10}$$

Equation (5) presents the aggregate demand constraint larger than quantity of items supplied over a fixed planning period. Equation (6) presents the vendor product capacity constraint based on the uncertain aggregate demand. Equation (7) presents the incorporate total item purchasing value constraint. Equation (8) presents the flexibility of the vendors' quota. Equation (9) presents the budgetary constraint where no vendor can exceed the budgeted allocated to vendors. Finally, Equation (10) presents the non-negativity constraint prohibiting negative orders. Generally, the tilde sign (~) indicates that the environment objectives function and constraints are fuzzy [29,30]. The fuzzy decision can be either symmetric or asymmetric depending on whether the objectives and constraints have equal or unequal weights [26,30,31]. These weights can be derived using techniques such as the AHP with a geometric mean (see details of the process in Chakraborty, Majumder; Sarkar, 2005) [32].

2.4. The Solution of the VSPLCC Procurement Problem Using the Weight Additive Approach

In this section, we present the general multi-objective model for solving the VS problem. To specify the weights of the goals and constraints in a fuzzy environment, we can use a fuzzy approach, instead of having the DM subjectively assign values to these weights. To obtain the supertransitive approximation of the previous comparison matrix, we construct supplementary matrices $A^1, A^2, \ldots, A^n$. The jth row of matrix A^j is the same as the jth row of the initial matrix A, where the supplementary matrix $(A^j)^{T*} = \left[a_1^j, a_2^j, \ldots, a_n^j\right]$ and each row of the matrix A^j is computed as follows (T^*: Transpose): $a_j^j = a_j$, $a_1^j = (a_{j1})^{-1}a_j^j, a_2^j = (a_{j2})^{-1}a_j^j, \ldots, a_n^j = (a_{jn})^{-1}a_j^{\cdot j}$. Next, we construct the supertransitive approximation, $A^s = \|a_{ij}^s\|$, $i, j = 1, 2, \ldots, n$, by taking the geometric mean of the corresponding elements from the supplementary matrices $A^1, A^2, \ldots, A^n$. More formally, $a_{ij}^s = (a_{ij}^1 \times a_{ij}^2 \times \ldots\ldots \times a_{ij}^n)^{\frac{1}{n}}$. Then we obtain the largest value of A^s with an eigenvector method. The corresponding eigenvector is the optimal weight for the criteria [26,33]. In the solution to the VSPLCC problem model, the AHP with weighted geometric mean (WGM) is calculated using a supertransitive approximation. Thus, these weights are assigned separately. In these equations, α_{jt} is the weighting coefficient that shows the relative importance at the four stages of the PLC.

The following crisp simplex objective programming function used to solve VSPLCC procurement problem.

Model 1: The weighted additive (WA) approach [34], which is formulated as follows:

$$\text{Max} \sum_{j=1}^{s}\sum_{t=1}^{4} \alpha_{jt}\lambda_{jt}^{*} \tag{11}$$

$$\text{s.t. } \lambda_{jt} \leq \mu_{zjt}(x),\ j = 1, 2, \ldots, q,\ t = 1, 2, 3, 4, \tag{12}$$

$$\gamma_{rt} \leq \mu_{hrt}(x),\ r = 1, 2, \ldots, h = 1, 2, 3, 4, \tag{13}$$

$$g_{mt}(x) \leq b_{mt},\ m = 1, \ldots, p,\ t = 1, 2, 3, 4, \tag{14}$$

$$\lambda_t \in \{0, 1\},\ t = 1, 2, 3, 4, \tag{15}$$

$$\sum_{j=1}^{s}\sum_{t=1}^{4} \alpha_{jt} = 1, \alpha_{jt} \geq 0,\ t = 1, 2, 3, 4, \tag{16}$$

$$x_{nt} \geq 0,\ n = 1, 2, \ldots, i = 1, 2, 3, 4. \tag{17}$$

See Amid et al. (2011) [35] for a more detail.

2.5. The Solution of the VSPLCC Procurement Problem Based on Lin's Weighted Max-Min Approach

Lin (2004) proved that a weighted max–min (WMM) approach could find an optimal solution such that the ratio of the achievement level approximates the ratio of the weight as closely as possible. He noted that the WA model gives heavier weights to objectives of higher achievement levels than do other models. However, the ratio of the achievement levels is not necessarily the same as that of the objectives' weights [35,36]. Thus, to obtain the solution of the VSPLCC procurement problem model, WMM model is used as follows:

Model 2: Lin's WMM approach (Lin, 2004) [36]:

$$\text{Max } \lambda_t, \tag{18}$$

$$\text{s.t. } w_{jt}\lambda_{jt} \leq \mu_{zjt}(x),\ j = 1, 2, \ldots, q,\ t = 1, 2, 3, 4, \tag{19}$$

$$\gamma_{rt} \leq \mu_{hrt}(x),\ r = 1, 2, \ldots, h = 1, 2, 3, 4, \tag{20}$$

$$g_{mt}(x) \leq b_{mt},\ m = 1, \ldots, p,\ t = 1, 2, 3, 4, \tag{21}$$

$$\lambda_t \in \{0, 1\},\ t = 1, 2, 3, 4, \tag{22}$$

$$\sum_{j=1}^{s}\sum_{t=1}^{4}\alpha_{jt} = 1,\ \alpha_{jt} \geq 0,\ t = 1, 2, 3, 4, \tag{23}$$

$$x_{nt} \geq 0,\ n = 1, 2, \ldots, i, = 1, 2, 3, 4. \tag{24}$$

2.6. The Solution of the VSPLCC Procurement Problem Based on MCGP Approaches

In real decision-making problems, goals are often interrelated in which DMs can set more aspiration levels using the idea of multi-choice aspiration level (MCAL) to find more appropriate resources so as to reach the higher aspiration level in the initial stage of the solution process (Chang, 2007) [27]. To address this issue, the MCGP AFM (achievement function model) models are developed below.

MCGP AFM (case I)(**Model 3**): The MCGP AFM (case I) is used in the case of "the more, the better" as follows. Minimize

$$\sum_{i=1}^{n}\sum_{t=1}^{4}\left[w_{it}(d_{it}^{+} + d_{it}^{-}) + \alpha_{it}(e_{it}^{+} + e_{it}^{-})\right]$$

$$\text{s.t. } f_{ti}(X)b_{it} - d_{it}^{+} + d_{it}^{-} = b_{it}y_{it},\ i = 1, 2, \ldots, ,\ t = 1, 2, 3, 4, \tag{25}$$

$$y_{it} - e_{it}^{+} + e_{it}^{-} = g_{it,\max},\ i = 1, 2, \ldots, n,\ t = 1, 2, 3, 4, \tag{26}$$

$$g_{it,\min} \leq y_{it} \leq g_{it,\max},\ i = 1, 2, \ldots, n\ t = 1, 2, 3, 4, \tag{27}$$

$$d_{it}^{+}, d_{it}^{-}, e_{it}^{+}, e_{it}^{-} \geq 0,\ i = 1, 2, \ldots, ,\ t = 1, 2, 3, 4. \tag{28}$$

$X \in F$ where F is a feasible set and X is unrestricted in sign. Where $b_{it} \in \{0, 1\}$ is a binary variable attached to $|f_{it}(X) - y_{it}|$, which can be either achieved or released in Equation (25). In terms of real conditions, b_{it} is subject to some appropriate constraints according to real needs.

MCGP AFM (case II) (**Model 4**): The MCGP AFM (case II) is used in the case of "the less, the better" as follows. Minimize

$$\sum_{i=1}^{n}\sum_{t=1}^{4}\left[w_{it}(d_{it}^{+} + d_{it}^{-}) + \alpha_{it}(e_{it}^{+} + e_{it}^{-})\right]$$

$$\text{s.t. } f_{ti}(X)b_{it} - d_{it}^{+} + d_{it}^{-} = b_{it}y_{it},\ i = 1, 2, \ldots, n,\ t = 1, 2, 3, 4, \tag{29}$$

$$y_{it} - e_{it}^{+} + e_{it}^{-} = g_{it,\max},\ i = 1, 2, \ldots, n,\ t = 1, 2, 3, 4, \quad (30)$$

$$g_{it,\min} \leq y_{it} \leq g_{it,\max},\ i = 1, 2, \ldots, n = 1, 2, 3, 4, \quad (31)$$

$$d_{it}^{+}, d_{it}^{-}, e_{it}^{+}, e_{it}^{-} \geq 0,\ i = 1, 2, \ldots, ,\ t = 1, 2, 3, 4. \quad (32)$$

where all variables are defined as in model 3. The mixed-integer terms Equations (29) and (32) can easily be linearized using the linearization method (Chang, 2008) [28]. As seen in Equations (25), (29)–(31), there are no selection restrictions for a single goal, but some dependent relationships exist among the goals. For instance, we can add the auxiliary constraint $b_{it} \leq b_{i+1,t} + b_{i+2,t}$ to the MCGP AFM, where b_{it}, $b_{i+1,t}$ and $b_{i+2,t}$ are binary variables. As a result, $b_{i+1,t}$ or $b_{i+2,t}$ must equal 1 if $b_{it} = 1$. This means that if goal 1 has been achieved, then either goal 2 or goal 3 has also been achieved.

2.7. The Solution Procedure of VSPLCC Procurement Problem

In order to solve the VSPLCC procurement problem, the following procedure is then proposed.

Step 1: Construct the model for VSPLCC procurement.

Step 2: A WGM technique is used to determine the criteria for MOLP model [37]. A WGM technique with a supertransitive approximation is used to obtain the binary comparison matrixes (Narasimhan, 1982) [33].

Step 3: Calculate the criteria of weighted geometric mean for solving VSPLCC procurement problem.

Step 4: Repeat the process individually for each of the remaining objectives. It determines the lower and upper bounds of the optimal values for each objective corresponding to the set of constraints.

Step 5: Use these limited values as the lower and upper bounds for the crisp formulation of the VSPLCC procurement problem.

Step 6: Based on Steps 4–5 we can find the lower and upper bounds corresponding to the set of solutions for each objective. Let Z_{jt}^{-} and Z_{jt}^{+} denote the lower and upper bound, respectively, for the *jt th* objective (Z_{jt}) (Amid, Ghodsypour; O'Brien, 2011) [35].

Step 7: Using the weighted geometric mean with a supertransitive approximation to solve Model 1 by following Equations (11)–(17).

Step 8: Formulate and solve the equivalent crisp model of the weighted geometric mean max-min for the VSPLCC procurement problem to solve Model 2 by following Equations (18)–(24).

Step 9: Use the weighted geometric mean and the no-PW (penalty weights) formulation of the fuzzy optimization problem to solve Model 3 by following Equations (25)–(28).

Step 10: Formulate Model 4 using the weighted geometric mean and the PW formulation of the fuzzy optimization problem by following Equations (29)–(32). Assume that the purchasing company manager sets a PW of five for a vendor missing the net cost goal, four for missing the rejection goal, three for missing the late deliveries goal, and two for exceeding the PLC cost goal (Chang, 2008) [28].

Step 11: The four stages of the PLC cost matrix are given as follows (Demirtas; Ustun, 2009) [37]:

$$\begin{pmatrix} 1.92 & 1.52 & 1.23 & 1.82 \\ 1.04 & 0.92 & 0.86 & 1.00 \\ 3.94 & 3.52 & 3.05 & 3.56 \end{pmatrix}$$

Step 12: Assume that the four stages of the PLC budget matrix are given as follows:

$$\begin{pmatrix} 25,000 & 26,500 & 27,400 & 26,000 \\ 100,000 & 120,000 & 125,000 & 110,000 \\ 35,000 & 36,000 & 37,500 & 35,200 \end{pmatrix}$$

Step 13: Solve the MOLP and MCGP models for the fuzzy optimization problem.

Step 14: Analyze the PLCCs and capacity limitations for the four stages. The procedure of the VSPLCC procurement problem-solving model is illustrated through a numerical example. Figure 2 shows the use of the AHP with a WGM and supertransitive approximation with a WGM technique to the MOLP and MCGP approach models to solve VSPLCC procurement problems.

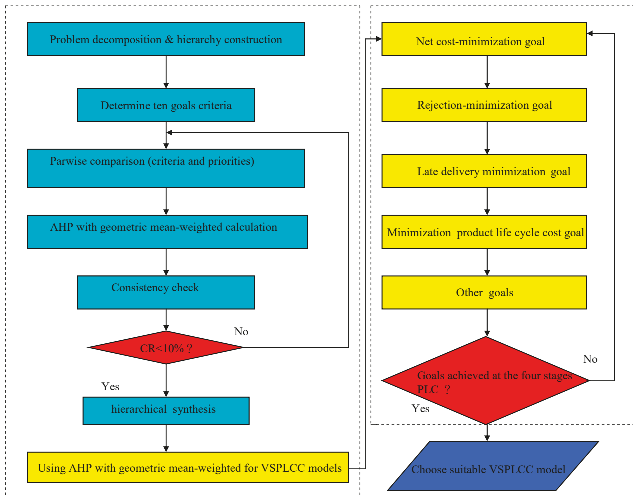

Figure 2. Using AHP and supertransitive approximation with a WGM algorithm with the MOLP and MCGP approach models to solve VSPLCC problems.

3. Numerical Example

As global warming intensifies, carbon dioxide emissions is an important issue in the warming caused by greenhouse gases. Reducing the greenhouse effect and protecting the Earth's environment are important goals associated with the use of white light-emitting diodes (LED) since they consume substantially less electrical power than other light sources. White-light LED power can reduce the amount of crude oil used in power plants and substantially reduce the generation of CO_2 emissions, which helps to significantly reduce contributions to the greenhouse effect. Thus, according to the estimate from the optoelectronics industry development association (OIDA), using white LED lighting technology could reduce emissions worldwide by 2.5 billion tons of CO_2 annually.

We used the VSPLCC procurement model to solve a real case in the distribution department for the Everlight Company (the leading LED manufacturer in Taiwan), which is part of a multi-national group in the LED research and development (R and D) sector. External purchases account for more than 75% of the total annual costs, and the firm works on a make-to-order basis. The company's management aimed to improve the efficiency of the purchasing process and reconsider the company's sourcing strategies. A manager felt that the company must evaluate and certify the company's vendors to ensure reductions in product inventory and time to market. The company sought to develop longer-term, trust-based relationships with a smaller group of vendors, and the company manager appointed a team to recommend three or four suitable vendors. This team consisted of several managers from various departments, including purchasing, marketing, quality control, production, engineering and R& D. The members of the team organized several meetings to create profiles for the competing vendors and constructed an initial set of three vendors for evaluation purposes. A VSPLCC procurement model was then developed to select the appropriate vendors and to determine their quota allocations in uncertain environments.

The team considered some objective functions and constraints as follows: Minimizing the net cost, minimizing the net rejections, minimizing the net late deliveries, minimizing the PLC cost, vendor capacity limitations, vendor budget allocations. The other considerations were: Price quoted (P_i in $), the percentage of rejections (R_i), the percentage of late deliveries (L_i), the PLCC (C_i), the PLC of the vendors' capacities (Ui), the vendors' quota flexibility (F_i, on a scale from 0 to1), the vendors' ratings (R_i, on a scale from 0 to 1), and the budget allocations for the vendors (B_i) were also considered.

The least amount of flexibility in the vendors' quotas is calculated as $Q = F \times D$, and the smallest total purchase value is calculated as $P = R \times D$. If the overall flexibility (F) is 0.03 on a scale of 0–1; if the overall vendor rating (R) is 0.92 on a scale of 0–1; and if the aggregate demand (D) is 20,000; then the least amount of flexibility in the vendors' quotas (F) and the smallest total purchase value of the supplied items (P) are 600 and 18,400, respectively. The three vendor profiles are shown in Table 2.

Table 2. Vendor source data for the problem.

Vendor No.	P_i ($)	R_i (%)	L_i (%)	C_i ($)	U_i (Units)	r_i	F_i	B_i ($)
1	3	0.05	0.04	1.92	5000	0.88	0.02	25,000
2	2	0.03	0.02	1.04	15,000	0.91	0.01	100,000
3	6	0.01	0.08	3.94	6000	0.97	0.06	35,000

In this case, the linear membership function is used to fuzzify the right-hand side of the constraints in the VSPLCC problem. The values of the uncertainty levels for all of the fuzzy parameters were taken as 10% of the corresponding values of the deterministic model. The datasets for the values at the lowest and highest aspiration levels of the membership functions are given in Table 3.

Table 3. Limiting values in the membership function for net cost, rejections, late deliveries, PLC cost, vendor capacities and budget information. (Data for all four stages: Introduction, growth, maturity, decline).

	(**min.**) μ=1	(**max.**) μ=0
Main Goals		
(G_1) Net cost objective	57,000	71,833
(G_2) Rejection objective	413	521
(G_3) Late deliveries objective	604	816
(G_4) PLC cost objective	10,000	90,000
(G_5) Vendor 1	5000	5500
(G_6) Vendor 2	15,000	16,500
(G_7) Vendor 3	6000	6600
Budget constraints		
(G_8) Vendor 1	25,000	27,500
(G_9) Vendor 2	100,000	110,000
(G_{10}) Vendor 3	35,000	38,500

3.1. Application of the WA Approach to the Numerical Example

We obtained the solution using the WA approach of Tiwari et al. (1987), and in the next section we show the procedure by using the WGM AHP to construct a WGM supertransitive approximation to obtain the binary comparison matrixes.

Using the WGM AHP with WGM Supertransitive Approximation to Solve the VSPLCC Procurement Problem

Before determining the solution, we determined the weights of the AHP with the geometric mean process (see Chakraborty et al. 2005 [32]). Evaluating and selecting vendors is a typical MCDM problem involving multiple criteria that can be formulated by both qualitative and quantitative [38].

The VS problem involves tangible and intangible criteria, which may vary depending on the type of product being considered and may include many judgmental factors [24,39,40].

These criteria are shown in Figure 3. The VSPLCC procurement problem addresses how optimally performing vendors can be selected given the desired criteria. The AHP is one of the most widely used MCDM methods; it can be used to handle multiple criteria. The criteria for the VS problem are shown in Table 4. Based on the ratings obtained using the questionnaire, the average matrix is shown in Table 5. The maximum value of the eigenvector for the above matrix λ_{max} is 10.77 [32]. The consistency index C.I. is given by $(\lambda_{max} - n)/(n - 1) = 0.09$. The random index for the matrix of order 10 [41,42]. R.I. is 1.49. The consistency ratio C.R. is given by C.I./R.I. = 0.06, which is not greater than 0.1 (<0.1 acceptable).

$$A \; = \Rightarrow \begin{pmatrix} 1 & 6 & 4 & 9 & 3 & 4 & 9 & 9 & 8 & 2 \\ 1/6 & 1 & 1/2 & 3 & 1/3 & 1/3 & 2 & 4 & 5 & 1/4 \\ 1/4 & 2 & 1 & 4 & 1/2 & 1/2 & 3 & 5 & 6 & 1/3 \\ 1/9 & 1/3 & 1/4 & 1 & 1/5 & 1/2 & 2 & 3 & 3 & 1/6 \\ 1/3 & 3 & 2 & 5 & 1 & 1 & 4 & 6 & 7 & 1/2 \\ 1/4 & 3 & 2 & 5 & 1 & 1 & 4 & 6 & 7 & 1/2 \\ 1/9 & 1/2 & 1/3 & 2 & 1/4 & 1/4 & 1 & 3 & 4 & 1/5 \\ 1/9 & 1/4 & 1/5 & 1/2 & 1/6 & 1/6 & 1/3 & 1 & 2 & 1/8 \\ 1/8 & 1/5 & 1/6 & 1/3 & 1/7 & 1/7 & 1/4 & 1/2 & 1 & 1/9 \\ 1/2 & 4 & 3 & 6 & 2 & 2 & 5 & 8 & 9 & 1 \end{pmatrix}$$

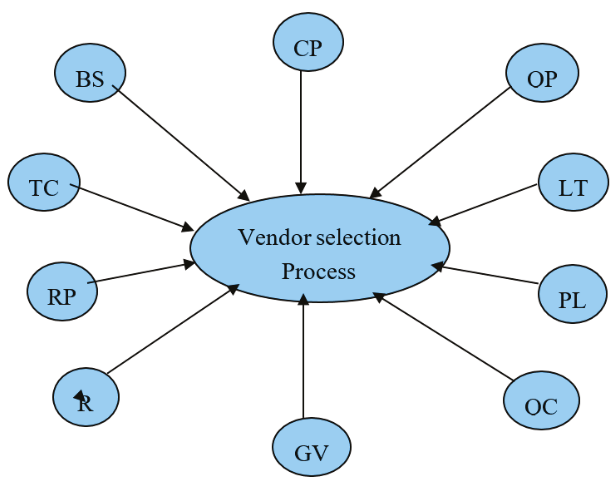

Figure 3. Criteria for the VSPLCC problem.

Table 4. VSPLCC criteria and abbreviations (adopted and modified from Kumar et al., 2009).

Criteria Number	Criteria	Abbreviation Used
1	Cost of product	CP
2	Quality of product (based on rejection rate)	QP
3	Lead time (late deliveries)	LT
4	PLC cost	PL
5	Quality certification of the vendor	QC
6	Goodwill of the vendor	GV
7	Reliability of the vendor	RV
8	Price of product	RP
9	Transportation ease and cost	TC
10	Buffer stock of inventory required	BS

Table 5. The geometric mean matrix for the criteria of the VSPLCC problems.

Criteria	CP	QP	LT	PL	QC	GV	RV	RP	TC	BS	RW	NW
CP	1	6	4	9	3	4	9	9	8	2	4.4939	0.2958
QP	0.167	1	0.500	3	0.333	0.333	2	4	5	0.250	0.8798	0.0579
LT	0.250	2	1	4	0.500	0.500	3	5	6	0.333	1.3110	0.0863
PL	0.111	0.333	0.250	1	0.200	0.500	2	3	3	0.167	0.5551	0.0365
QC	0.333	3	2	5	1	1	4	6	7	0.500	1.9608	0.1291
GV	0.250	3	2	5	1	1	4	6	7	0.500	1.9052	0.1254
RV	0.111	0.500	0.333	2	0.250	0.250	1	3	4	0.200	0.5949	0.0392
RP	0.111	0.250	0.200	0.500	0.167	0.167	0.333	1	2	0.125	0.3026	0.0199
TC	0.125	0.200	0.167	0.333	0.143	0.143	0.250	0.500	1	0.111	0.2288	0.0151
BS	0.500	4	3	6	2	2	5	8	9	1	2.9612	0.1949
Total	2.9583	20.2833	13.45	35.833	8.5929	9.8929	30.5833	45.5	52	5.1861	15.1933	1.000

The AHP process with a geometric mean was applied to this comparison matrix, and the following weights were obtained [33]: $w_1 = 0.2958$, $w_2 = 0.0579$, $w_3 = 0.0863$, $w_4 = 0.0365$, $w_5 = 0.1291$, $w_6 = 0.1254$, $w_7 = 0.0392$, $w_8 = 0.0199$, $w_9 = 0.0151$, and $w_{10} = 0.1949$ (see Section 4.1: Using the AHP process with a geometric mean).

The supertransitive approximation method is only used with the WA approach with a geometric mean to matrix A. Supertransitive approximation matrix A is constructed using the following algorithm described in Section 3.2: Solution to the VSPLCC procurement problem via the WA approach. The ten supplementary matrices corresponding to A are:

$$A = \begin{bmatrix} 1 & 5.1080 & 3.4278 & 9.2397 & 2.2919 & 2.5851 & 8.6768 & 15.4672 & 19.6386 & 1.3830 \\ 0.1958 & 1 & 0.6711 & 3 & 0.3333 & 0.3333 & 2 & 4 & 4.5622 & 0.25 \\ 0.2917 & 1.4902 & 1 & 4 & 0.5 & 0.5 & 3 & 3.6239 & 4.2701 & 0.3333 \\ 0.1082 & 0.3333 & 0.25 & 1 & 0.2 & 0.3789 & 0.2192 & 3 & 1.6161 & 0.1667 \\ 0.4363 & 3 & 0.7579 & 5 & 1 & 1 & 4.0903 & 6 & 7 & 0.5 \\ 0.3868 & 3 & 2 & 5 & 1 & 1 & 3 & 6 & 7 & 0.5 \\ 0.1153 & 0.5 & 0.2805 & 1 & 0.25 & 0.3333 & 1 & 2.8808 & 4 & 0.2 \\ 0.0647 & 0.25 & 0.2 & 0.5 & 0.1667 & 0.1667 & 0.3471 & 1 & 2 & 0.125 \\ 0.0509 & 0.2 & 0.1667 & 0.3333 & 0.1429 & 0.1429 & 0.25 & 0.5 & 1 & 0.1111 \\ 0.7231 & 4 & 3 & 6 & 2 & 2 & 5 & 8 & 9 & 1 \end{bmatrix}$$

The supertransitive approximation method was applied to this comparison matrix, and the ollowing weights were obtained: $w_1 = 0.3020$, $w_2 = 0.0611$, $w_3 = 0.0810$, $w_4 = 0.0272$, $w_5 = 0.1226$, $w_6 = 0.1294$, $w_7 = 0.0376$, $w_8 = 0.01936$, $w_9 = 0.0142$, and $w_{10} = 0.2057$ and its corresponding eigenvalue λ_{max} is 9.94 [33]. Table 6 shows the AHP method weight with geometric mean and the supertransitive approximation with the geometric mean. For this VSPLCC procurement problem, we obtained the optimal quota allocations (i.e., the purchasing order), vendor product capacity limitations, and the budget constraints of the different vendors by using the WA approach model (i.e., Model 1) in accordance with Equations (11)–(17).

Table 6. AHP method weight and supertransitive approximation with geometric mean.

Criteria Number	Criteria	AH AHP Method Weight $\lambda_{max} = 10.77$	Supertransitive Proximation $\lambda_{max} = 9.94$
1	CP	0.2958	0.3020
2	QP	0.0579	0.0611
3	LT	0.0863	0.0810
4	PL	0.0365	0.0272
5	QC	0.1291	0.1226
6	GV	0.1254	0.1294
7	RV	0.0392	0.0376
8	RP	0.0199	0.0193
9	TC	0.0151	0.0142
10	BS	0.1949	0.2057

3.2. Using Lin's WMM Approach to Solve the Numerical Example

For this VSPLCC procurement problem illustrative example, we obtained the optimal quota allocations (i.e., the purchasing order) subject to vendor product capacity limitations and budget constraints among the different vendors with Lin's WMM [36].

3.2.1. Using a MCGP AFM (Model 3: Case I) to Solve the Numerical Example

For this VSPLCC procurement problem, we obtained the optimal quota allocations (i.e., the purchasing order), supplier product capacity limitations and budget constraints among the different vendors by using the MCGP method and a no-PW approach (according to Equations (25)–(28)). This VSPLCC problem was then formulated as follows (using the first stage of the PLC for Model 1):

$$\begin{aligned}\text{Max} \;=\; & 0.2958\lambda_1 + 0.0579\lambda_2 + 0.0863\lambda_3 + 0.0365\lambda_4 + 0.1291\lambda_5 + 01254\lambda_6 + 0.0392\lambda_7 \\ & + 0.0199\lambda_8 + 0.0151\lambda_9 + 0.1949\lambda_{10}\end{aligned}$$

Main Goals:

$$(G_{11})\; 3x_{11} + 2x_{21} + 6x_{31} \;=\; 57{,}000\; (G11,_{\text{ MIN}}.) \text{ or } 71{,}833\; (G11,_{\text{ MAX}}.),$$

$$(G_{21})\; 0.05x_{11} + 0.03x_{21} + 0.01x_{31} \;=\; 413\; (G_{21},\; _{\text{MIN}}.) \text{ or } 521\; (G_{21},\; _{\text{MAX}}.),$$

$$(G_{31})\; 0.04x_{11} + 0.02x_{21} + 0.08x_{31} \;=\; 604\; (G_{31},\; _{\text{MIN}}.) \text{ or } 816\; (G_{31},\; _{\text{MAX}}.),$$

$$(G_{41})\; 1.92x_{11} + 1.04x_{21} + 3.94x_{31} \;=\; 10{,}000\; (G_{41},\; _{\text{MIN}}.) \text{ or } 90{,}000\; (G_{41},\; _{\text{MAX}}.).$$

Capacity Constraints Goals:

$$(G_{51})\; x_{11} \;=\; 5000\; (G_{51},\; _{\text{MIN}}.) \text{ or } 5500\; (G_{51},\; _{\text{MAX}}.)\; (X_{11},\; \text{Vendor 1's product capacity}),$$

$$(G_{61})\; x_{21} = 15{,}000\; (G_{61},\; _{\text{MIN}}.) \text{ or } 165{,}000\; (G_{61},\; _{\text{MAX}}.)\; (X_{21},\; \text{Vendor 2's product capacity}),$$

$$(G_{71})\; x_{31} = 6000\; (G_{71},\; _{\text{MIN}}.) \text{ or } 165{,}000\; (G_{71},\; _{\text{MAX}}.)\; (X_{31},\; \text{Vendor 3's product capacity}),$$

$$x_{11} + x_{21} + x_{31} = 20{,}000\; (\text{Total demand constraint}).$$

Budget Constraints Goals:

$$(G_{81})\; 3x_{11} = 25{,}000\; (G_{81},\; _{\text{MIN}}.) \text{ or } 27{,}500\; (G_{81},\; _{\text{MAX}}.)\; (X_{11},\; \text{Vendor 1's budget constraint}),$$

$$(G_{91})\; 2x_{21} = 100{,}000\; (G_{91},\; _{\text{MIN}}.) \text{ or } 110{,}000\; (G_{91},\; _{\text{MAX}}.)\; (X_{21},\; \text{Vendor 2's budget constraint}),$$

$$(G_{101})\; 6x_{31} = 35{,}000\; (G_{101},\; _{\text{MIN}}.) \text{ or } 110{,}000\; (G_{101},\; _{\text{MAX}}.)\; (X_{31},\; \text{Vendor 3's budget constraint}).$$

3.2.2. Using a MCGP AFM (Model 4: Case II) to Solve the Numerical Example

The subjectivity inherent to the determination of both the desired level of attainment for each goal and the penalty weights assigned to deviations from the goal may present a problem [19,36]. Suppose that the purchasing company's manager sets a penalty weight of five for the vendor missing the net cost goal, four for missing the rejection goal, three for missing the late deliveries goal, and two for exceeding the PLC cost goal [28]. For this VSPLCC procurement problem, we obtained the optimal quota allocations (i.e., the purchasing order), supplier product capacity limitations and budget constraints among the different vendors using the MCGP method and a PW approach in accordance with Equations (29)–(32). 4. Solution Results of the Two Types of MOLP and MCGP Model Approaches.

4. Solution Results of the Two Types of MOLP and MCGP Model Approaches

After using the Lingo 11.0 software package solving the VSPLCC procurement problem, we found that Lin's (2004) [36] WMM approach and the MCGP method with the geometric mean and the PW approach have the same results in the first stage of the PLCs. With regards to the MCGP approaches with the geometric mean (no-PW restrictions), x_{11} = 5000 (due to the absence of PW constraints), $b_{11} = 1$ and $b_{51} = 1$. The forced bound order quantity of vendor 1 was 5000 (i.e., for model 3 at the first stage (Introduction), x_{11} = 5000) (see Tables 7–11). With regards to the other approaches (i.e., the MCGP approach with the geometric mean and the PW approach), $b_{12} = 1$ and $b_{62} = 1$. The forced bound order quantity of vendor 2 was greater than 15,000 (i.e., for model 4 at the second period (Growth), x_{22} = 15,750). To guarantee the net cost goal, the rejection goal, or the late delivery goal, zero value should be achieved (e.g., if $b_{12} = 1$ and $b_{62} = 1$, then forces b_{it} equal to zero used to adjust the purchasing quantity) (see Tables 8–12). We found the MCGP model to be stable with regard to the PLCC in all of the stages (see Tables 13–15).

Table 7. PLCC model during the first stage (Introduction).

	Z_1	Z_2	Z_3	Z_4
Model 1	57,000	521	656	33,162
Model 2	57,000	515	655	33,125
Model 3	72,980	560	920	45,486
Model 4	72,980	560	920	45,486

Table 8. PLCC during the second stage (Growth).

	Z_1	Z_2	Z_3	Z_4
Model 1	57,000	521	656	29,438
Model 2	57,000	515	655	29,450
Model 3	71,980	440	880	39,187
Model 4	57,000	515	655	29,450

Table 9. PLCC during the third stage (Maturity).

	Z_1	Z_2	Z_3	Z_4
Model 1	57,000	521	656	26,465
Model 2	57,000	515	655	26,508
Model 3	71,980	440	880	34,709
Model 4	57,000	515	655	26,507

Table 10. PLCC during the fourth stage (Decline).

	Z_1	Z_2	Z_3	Z_4
Model 1	57,000	521	656	30,923
Model 2	57,000	515	655	30,880
Model 3	71,980	440	880	40,467
Model 4	57,000	515	655	30,880

Table 11. PLCC during the first period (Introduction).

	Order Quantity x_1	Order Quantity x_2	Order Quantity x_3
Model 1	240	5570	4190
Model 2	0	5570	4250
Model 3	5000	8005	6995
Model 4	0	15,750	4250

Table 12. PLCC during the second period (Growth).

	Order Quantity x_1	Order Quantity x_2	Order Quantity x_3
Model 1	240	15,570	4190
Model 2	0	12,005	7995
Model 3	0	12,005	7995
Model 4	0	15,7500	4250

Table 13. All of the models for order quantity of vendor x_1 in the fourth PLC stages.

Stages of PLC	Model 1	Model 2	Model 3	Model 4
Introduction	240	0	5000	0
Growth	240	0	0	0
Maturity	240	0	0	0
Decline	240	0	0	0

Table 14. All of the models for order quantity of vendor x_2 in the four PLC stages.

Stages of PLC	Model 1	Model 2	Model 3	Model 4
Introduction	15,570	15,570	8005	15,570
Growth	15,570	12,005	12,005	15,750
Maturity	15,570	15,750	12,005	15,750
Decline	15,570	15,750	12,005	15,750

Table 15. All of the models for order quantity of vendor x_3 in the four PLC stages.

Stages of PLC	Model 1	Model 2	Model 3	Model 4
Introduction	4190	4250	6995	4250
Growth	4190	7995	7995	4250
Maturity	4190	4250	7995	4250
Decline	4190	4250	7995	4250

4.1. Analysis of Results

Based on the solutions to the two type's goal-programming models, after using the Lingo 11.0 software package we summarized the results of the VSPLCC procurement problem in Tables 7–15. From Z_{4t} (i.e., the PLC cost goal) of Figure 4, we can see that the maturity stage has the lowest PLC cost; in contrast, the growth and decline stages have similar costs, and the introduction stage has a high PLC cost. We found that the MCGP model demonstrated more stable control of the PLC cost over all of the stages.

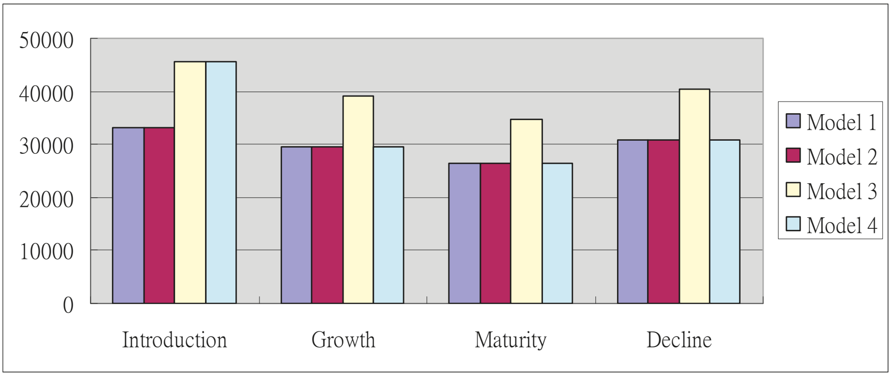

Figure 4. Z_{4t}: The results of the four VSPLCC models' solutions to the PLCC goal.

5. Conclusions and Managerial Implications

5.1. Conclusions

The results obtained using the MOLP and MCGP VSPLCC procurement problem models for determining vendor quotas in SCM if the capacity and budget constraints of each vendor are not known with certainty. The effectiveness of the VSPLCC procurement model was demonstrated with a real-world problem adopted from a leading LED company in Taiwan. Managers in high-tech companies can easily apply our VSPLCC procurement model to select their vendors in a fuzzy environment using the MOLP and MCGP approaches. We found in our study results that the weighted geometric mean with AHP and PW methods has good control conditions for constructing an MCGP AFM model (model 4) within four PLC stages.

5.2. Managerial Implications

Some managerial implications are found as follows: (i) doing so is practical because the no-PW and PW MCGP AFM model approaches (MCGP AFM models 3 and 4) do not require precise knowledge of all of the parameters, and they make the application of a fuzzy methodology more understandable [27,28,35]; (ii) the No-PW and PW MCGP models are demonstrated to be more stable over all of the PLC stages; (iii) company managers can easily use MOLP and MCGP model approaches to solve VSPLCC procurement problems; and (iv) this VSPLCC procurement model allows DMs to solve VSPLCC problems when considering their preferences.

5.3. Limitations

We integrate VS and PLCC procurement planning into a VSPLCC procurement model for enterprise to reduce their purchasing costs. In order to eliminate the MOLP and MCGP model approaches drawbacks and achieve the accurate results, we are comparing two GP with AHP supertransitive approximation with a WGM technique to verify the result of the VSPLCC procurement model. Otherwise, if DMs use a new AHP method and conjunction GP approach, it can be a different result in uncertain conditions.

5.4. Future Directions

In addition, integrating other mathematical models, such as the Pareto concept with AHP and ANP [37,43] with DEAHP [44], or AHP-QFD [45] with the MOGP [46] and MCGP [27,28,47] models to solve the VSPLCC procurement problems in a multi-item—multi-vendor environment that could be performed in conjunction with the various models [48].

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Effects of Human Factors and Lean Techniques on Just in Time Benefits

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Abstract: A successful Just in Time (JIT) implementation is based on human resources integration (managers, operators and suppliers) and other lean manufacturing techniques applied in the production process. However, the relationship between these variables is not easily quantified. This paper reports a structural equation model that integrates variables associated with JIT implementation: management commitment, human resources integration, suppliers and production tools and technique, which affect the benefits gained, and are integrated into nine hypotheses or relationships among then. The model is evaluated with information from 352 responses to a questionnaire applied to manufacturing industry, and partial least squares technique is used to evaluate it. The direct effects, sum of indirect effects, and total effects are quantified, and a sensitivity analysis based on conditional probabilities is reported to know scenarios associated with low and high levels in variables' execution and how they impact the benefits obtained. Findings indicate that managerial commitment is the most important variable in the JIT implementation process, since managers are the ones that determine the relationships with suppliers, integrate human resources, and approve the lean manufacturing techniques and tools that support the JIT.

Keywords: JIT implementation; suppliers in JIT; operational benefits; human factor in JIT; material flow; structural equation model

1. Introduction

Nowadays, industrial product markets are globalized, which implies that manufacturers are usually based in one region, whereas customers may be in another. However, this globalization phenomenon has expanded to entire production systems, and as a result, many components of the same final product are often manufactured abroad. This resource optimization strategy, which many production systems adopt nowadays, involves handling product subassemblies and materials along an assembly line in a factory [1], which is usually strategically located close to its target market [2]. Unfortunately, the raw materials and parts transportation process generates costs that add no value to the final product and compromises the economical and green sustainability of companies. Moreover, the highest rates of losses and accidents occur at this stage, as a result of transportation delays, material mishandling, and perished goods, to name but a few factors. In fact, logistics and transportation costs can represent up to 70% of a final product's costs. In this sense, effective supply chain management (SCM) is a source of economic savings for improved sustainable indexes.

The supply chain (SC) is the network of activities, facilities, and distribution channels that are necessary to create and sell a product. An SC involves looking for and extracting raw materials, transporting these materials to a factory, distributing the final product, and delivering it to the final customers [3]. The management process of all these activities is known as SCM, which relies on a wide range of production tools, techniques, and philosophies aimed at reducing costs and increasing sustainability. One of the popular techniques is Just in Time (JIT), which supports the processes of raw material supply, transformation, and distribution as a final product [4]. Overall, JIT supports the production process by seeking to eliminate unnecessary supply-related costs, reduce machine downtimes, and ensure a correct flow in the production process, increasing economical and green sustainability. As a result of these actions, both administrative and operational costs are significantly reduced [5], which has a positive impact on the costs of a final product; however, JIT is supported by other techniques, such as Kanban [6], just in sequence (JIS) [7], cell production, operations standardization, line balancing, among others [8].

JIT as a technique aims at eliminating waste in the production process. In this sense, multiple research works have reported the benefits gained after a successful JIT implementation. For instance, García-Alcaraz, et al. [9] identified 31 JIT benefits in the production process, including increased productivity, increased product quality, increased employee motivation, less waste and rework, better process efficiency, better teamwork, greater process flexibility, reduced fixed costs, reduced manpower costs, lower space requirements, reduced inventory, reduced overhead expenses, reduced movement distances, improved resource utilization, less paperwork, less material handling, better supplier–customer relationships, and shorter lead times, among other things.

JIT benefits are appealing to production managers, yet the question is usually how to implement a JIT system in such a way as to obtain all its benefits and improve SC integration and increase sustainability. In other words, it is important to identify the critical success factors (CSFs) that ensure a successful JIT implementation. Fortunately, several works have explored this trend. In their research, Garcia-Alcaraz, et al. [10] reported 14 CSFs for JIT, including production strategy, *Managerial Commitment* (*MAC*), employee commitment and management, relationships with *Suppliers* (*SUP*), employee education and training in JIT, plant layout, organizational aspects related to JIT, sales and distribution system, corporate plans and environmental policies, among others (observe that in the document the latent variables appear in italics).

JIT is viewed more as a production philosophy than as a production technique, since its cornerstones are *Human Resources Integration* (*HRI*), including *SUP*, managers, and operators [11]. Also, Priestman [12] relates JIT with statistical quality control, whereas to Balakrishnan, et al. [13], the philosophy can be associated with customer loyalty costs. On the other hand, Cua, et al. [14] claim that JIT is not an isolated technique because it works along with techniques such as total quality management (TQM) and total productive maintenance (TPM). Finally, Fullerton, et al. [15] declare that JIT has a direct association with economic benefits, whereas Maiga and Jacobs [16] explored JIT on overall corporate performance.

Recent works have explored the benefits of JIT from different perspectives. For instance, Inman, et al. [17] found an important relationship between JIT and both *Operational Benefits* (*OBE*) and corporate performance. Likewise, García, et al. [18] link the JIT philosophy to economic benefits, while Green Jr, et al. [19] found that SC efficiency indices and organizational performance are positively affected by JIT.

JIT as an industrial technique is of academic interest, specifically at the integration stage of globalized corporations, since it has the potential to reduce production costs associated with both logistics and transportation, and as consequence, improve sustainability indexes. However, most research works consider JIT as a whole and do not break it down into its CSFs. As a result, these works focus merely on the operational and technical aspects of JIT. Moreover, few works have quantified the relationship between the CSFs from JIT and their corresponding benefits, or have performed a sensitivity analysis on the different states of the variables. To address these gaps, our research seeks to explore the effects of human factors on JIT benefits under a quantitative perspective. Namely, we seek to find a measure of dependency between the analyzed CSFs and their corresponding JIT benefits. Moreover, we aim at reporting the likelihood of occurrence of the dependent variables with respect to changes in the independent variables.

This research assumes that JIT is a production philosophy, and human resources are responsible for implementing it in production systems. Consequently, our work focuses on identifying and measuring the effects of human factors in the performance of companies that implement JIT. Specifically, we propose a structural equations model that integrates five main variables: *MAC*, *SUP*, *HRI*, *TTP* and *OBE*. Additionally, we study as the mediating variable the presence of other manufacturing tools in the production process. We justify the presence of this mediating variable with the claim that JIT is not an isolated tool, as it works along with other tools, such as TPM, TQM, and Single-Minute Exchange of Dies (SMED) [18], to name but a few. The remainder of this paper is organized as follows: the next section discusses a literature review and presents the research hypotheses. Then, Section 3 describes the research methodology, whereas Section 4 discusses the results. Finally, Section 5 concludes with a series of final remarks and industrial implications.

Based on the above issues, there are two main contributions in this research, the first is that using a structural equation model, real and empirical data analyses are used to quantify the relationship between *MAC*, *SUP*, *HRI*, *TTP* with *OBE* gained after a JIT implementation. The relationships between these variables are expressed as measures of dependence between them, which allows managers to focus their efforts on activities that facilitate to obtain the benefits in their own context, excluding those that are trivial. In this sense, this research is-based critical success factor for JIT identified in literature and proposes a causal model that relates them and is not limited only to their identification and description.

The second contribution of this research is that a sensitivity analysis is provided, reporting the conditional probabilities that certain scenarios will occur when latent variables associated with human resources in the JIT execution process have low and high implementation levels and the benefits have been obtained in low and high levels. This analysis allows managers to identify risk attributes that support obtaining a desired benefit and on which they must focus their attention, such as sustainability. It is important to mention that this type of analysis has not been previously reported in studies conducted with causal models in the manufacturing industrial sector.

2. Literature Review and Research Hypotheses

As Singh and Garg [20] point out, worrying about *MAC*, *HRI*, and *TTP* is pointless if companies do not obtain benefits as a result of JIT implementation. According to Iqbal, et al. [21], corporate performance is the result of programs such as TQM and JIT, and top managers are responsible for determining the right implementation strategy for these programs, specifically for human factors and several authors has reported their importance. Table 1 collects a list of papers related to JIT and HR in industry (in this research, JIS is considered to be part of JIT), indicating that there is a direct relationship between them, the SC, and company performance.

Given the importance of HR in JIT implementation, the following paragraphs describe in a more detailed way the role of the manager, the suppliers, the operator integration, and the production tools and techniques used for guaranteeing success.

Table 1. Human resources in JIT implementation success.

Author	Findings
García-Alcaraz, et al. [22]	• JIT is a philosophy based on human resources • Training and investment in incentives are required • JIT increases job satisfaction, teamwork and HR efficiency
Monden [23]	• JIT must have respect for humanity • Human factors guarantee quality and JIT • Suppliers must be certified on quality for prevent productions stoppages.
Bányai and Bányai [24]	• JIS is a supply strategy supported by HR and improve their utilization • JIS is an evolution from JIT and requires HR • JIS must be applied to whole supply chain as a holistic program
Helms, et al. [25] and Oliver [26]	• HR are the most important factor in JIT implementation • Manager must focus in HR for warrantee JIT success
Power and Sohal [27]	• Report a literature review considering HR as an important variable in JIT implementation • JIT is based on HR as philosophy
Power and Sohal [28]	• Report the importance of HR for JIT in Australia • Training and education in HR support JIT and company performance
Yang and Yang [29]	• The Toyota Production System is based on HR, integrated by managers, operators, suppliers and customers.
Lytton, et al. [30]	• JIT as technique support the long-term network among partner in a production system

2.1. Managerial Commitment (MAC) in JIT Implementation

JIT can be implemented in the production process only if managers approve it. For Kumar and Garg [31], top managers are responsible for defining the company's JIT implementation strategy and integrating all the participants into the process, including *SUP* and operators. Similarly, Singh and Garg [20] claim that *MAC* is a key element for JIT systems, and production process engineers must inform managers of the benefits obtainable from JIT. In their work, Montes [32] performed a factor analysis on data gathered from manufacturing companies and found that *MAC* was the most important CSF for successful JIT implementation, since it could be associated with the performance of all the other factors, including *SUP*, employees, and JIT training. Additionally, the authors found that middle managers provided great support to the organizational structure, as they served as the link between top managers and operators.

To measure *MAC*, we relied on the following aspects [17,18,31,33]:

- *MAC1*. Communication and coordination between departments and suppliers.
- *MAC2.* Supervisors promote teamwork by encouraging operators to cooperate and express their opinions.
- *MAC3.* Managers, engineers, and operators frequently interact among them.
- *MAC4.* Senior management culture promotes timely compliance of projects.

2.2. Suppliers (SUP)

The flow of materials in a SC is only guaranteed with the involvement of *SUP*, who are responsible for delivering the raw materials to the manufacturer and keeping JIS in the production lines, avoiding delivery delays [34]. In this sense, delivery times are important, since supply delivery delays automatically trigger both production delays and late final product deliveries. It is thus known that *SUP* must be fully integrated in the SC, and this task is a managerial responsibility [35]. Similarly, having reliable *SUP* reduces uncertainty in the supply process [36], which is why managers must attempt to maintain long-term contracts with trusted, certified *SUP* [37].

To measure *SUP* integration in a JIT implementation environment, the following elements are assessed [20,31,32,38]:

- *SUP1. SUP* are integrated in the company using a pull strategy.
- *SUP2. SUP* deliver raw materials on time.
- *SUP3.* The manufacturing company holds long-term contracts with its *SUP*.
- *SUP4. SUP* are certified.
- *SUP5.* The company relies on a reduced number of *SUP*.

Since several *Supplier*-related activities depend on *MAC*, the first research hypothesis states as follows:

H1. *Managerial Commitment has a positive direct effect on Suppliers in the JIT implementation process.*

2.3. Human Resources Integration (HRI)

Line production supervisors and operators play a key role n the implementation of the JIT philosophy. Researchers such as García, Rivera, Blanco, Jiménez and Martínez [18] found that both training and skills development increased operator empowerment during the JIT implementation process, and Bányai, et al. [39] indicated the importance of human resource strategy for JIS, maintaining material flow along the SC; however, the allocation of resources necessary to these training programs depends on managers [40]. In this sense, senior managers must prioritize training projects focused on employee multifunctionality as an strategy [41]. Moreover, it has been found that investing in human resources training has a positive effect on SC flexibility and agility [42], and thus on the implementation of JIT keeping JIS in production lines.

However, as experts point out, companies should also promote job rotation to increase motivation among employees and offer them new challenges, where they can develop new skills and support waste reducing, but also, for increase the JIS and reducing buffers between work stations [24,39]. Likewise, as Esmaeilian, et al. [43] claim, managers must encourage teamwork during the JIT implementation process, especially during decision-making and problem-solving processes, to preserve support material flow in a JIS.

To measure *HRI* in JIT implementation, the following items are analyzed [20,31,32]:

- *HRI1.* Human resources are trained in multifunctional tasks.
- *HRI2.* The company has a job rotation program.
- *HRI3.* Employees are hired because of their problem solving and teamwork skills.
- *HRI4.* The company has specific work teams to solve production-related problems.
- *HRI5.* Employees are rewarded when they learn new skills.
- *HRI6.* Employees suggest solutions to machine and equipment problems.

Since most *HRI* tasks depend on *MAC*, the second research hypothesis can be proposed as follows:

H2. *Managerial Commitment has a positive direct effect on Human Resources Integration in the JIT implementation process.*

2.4. Production Tools and Techniques (TTP)

JIT is not an isolated technique, but is rather implemented along with other lean manufacturing techniques that help ensure a continuous flow of materials along the production system. To measure this construct, the following items are considered [16,19,20,31,33]:

- *TTP1.* The plant is organized in manufacturing cells or technology groups.
- *TTP2.* Machines are small, flexible, and can be moved.
- *TTP3.* The company has a Kanban system for control production.
- *TTP4.* The company implements a Poka-Yoke system for error prevention.
- *TTP5.* Both JIT and MRP are used for production planning and control.

- *TTP6.* The production program is leveled.
- *TTP7.* The product manufacturing flow is continuous within the value chain.
- *TTP8.* Processes are standardized.

Implementing these techniques requires extensive commitment, both inside and outside of the company. For instance, plant layout depends on what managers decide is best [44], whereas Material Requirements Planning (MRP) is usually implemented along JIT—and again, the top management department decides how many resources will be allocated to such a project [45]. As for Kanban-JIT implementation plans, they are generally a decision of production managers and senior managers [46]. In other words, the *TTP* being implemented in a given production system are subjected to managerial decisions. In this sense, the third research hypothesis can read as follows:

H3. *Managerial Commitment has a positive direct effect on Production Tools and Techniques in the JIT implementation process*.

As Iqbal, Huq and Bhutta [21] claim, well-integrated *SUP* contribute to an effective pull system, thereby increasing both SC flexibility/agility and product quality. Moreover, David and Eben-Chaime [47] found that *SUP* play a key role in manufacturing standards, which is why supplier-manufacturer relationships must be close and direct, and the number of trusted *SUP* should be as reduced as possible. Furthermore, *SUP* must be integrated in the manufacturer's MRP system to simplify real-time information sharing and decision making processes [48]. From this perspective, it can be argued that *TTP* can be associated with *SUP*, making it possible to propose the fourth research hypothesis as follows:

H4. *Suppliers have a positive direct effect on Production Tools and Techniques in the JIT implementation process*.

Successful *TTP* do not emerge overnight. In their research, conducted in the aerospace industry, Martínez-Jurado, et al. [49] found that human resources were the cornerstone of lean manufacturing plans and projects. Such findings are consistent with those reported by Jabbour, et al. [50], who qualitatively explored the relationship between human resources and the implementation of lean manufacturing tools in the automotive industry. In conclusion, since a good *HRI* is associated with the success of *TTP*, the fifth research hypothesis can be proposed as follows:

H5. *Human Resources Integration has a positive direct effect on Production Tools and Techniques in the JIT implementation process*.

2.5. Operational Benefits of JIT (OBE)

It would be useless to allocate time and resources to implement particular *TTP* if they did not bring any benefits in production systems. In their work, Kumar and Garg [31] reported a list of JIT benefits identified in Indian manufacturing companies, whereas Maiga and Jacobs [16] discussed the main effects of JIT on corporate performance. Likewise, other studies have explored JIT benefits in industrial manufacturing companies [9,32].

This research focuses particularly on the *OBE* that can be gained from successful JIT implementation. To assess this construct, the following items are measured [16,19,20,31,32]:

- *OBE1.* Raw material inventory levels decrease.
- *OBE2.* Work in process (WIP) inventory levels decrease.
- *OBE3.* Finish product inventory levels decrease.
- *OBE4.* Inventory turnover increases.
- *OBE5.* Lead times are shorter.
- *OBE6.* Production flexibility increases.
- *OBE7.* Waste levels decrease.

This list of JIT benefits can be attractive to many managers, whose responsibility thus becomes to promote the implementation of a JIT system and monitor its progress and further evolution into tools such as Seru, popularly implemented in Japan for line balancing [51]. However, such evolutions only occur once a given JIT system has reached a maximum level of maturity and thus offers the expected benefits. In this sense, Singh and Garg [20] argue that top management is the cornerstone of JIT maturity. Consequently, the sixth research hypothesis can be formulated as follows:

H6. *Managerial Commitment has a positive direct effect on Operational Benefits in the JIT implementation process.*

Many studies acknowledge the role of *SUP* in operational performance, yet few of them introduce JIT as the mediating variable. Experts argue that top management departments must select *SUP* that support the company's production strategy. This involves taking into account attributes such as quality certifications and commitment [52], compliance with delivery times [35], and sustainability, among other things [38]. Additionally, as Mendoza-Fong, et al. [53] claim, *SUP* must comply with specific attributes to contribute to the implementation of a solid JIT system. In other words, JIT implementation is not feasible without the support of *SUP*, since they are the start of the supply chain, as Shnaiderman and Ben-Baruch [35] state, but can also be a source of risk for SC [54]. Following this discussion, the seventh research hypothesis can be formulated as follows:

H7. *Suppliers have a positive direct effect on Operational Benefits in the JIT implementation process.*

HRI is at the core of the JIT philosophy and its benefits. In their work, García, et al. [55] developed a structural equations model and demonstrated that human resources training and education are associated with corporate performance. Additionally, García-Alcaraz, Macías, Luevano, Fernández, López and Macías [9] found that JIT benefits reflect on human resources, who expect some type of reward for their efforts in the implementation and maintenance of the philosophy. Finally, in their literature review, Singh and Garg [20] placed human factors as the top element for JIT implementation, which is consistent with what authors Kumar and Garg [31] reported in their work. From this perspective, our eighth research hypothesis is proposed below:

H8. *Human Resources Integration has a positive direct effect on Operational Benefits in the JIT implementation process.*

JIT benefits are also the result of the *TTP* implemented within manufacturing companies. In this sense, Ho and Chang [45] and Wang, Gong and Wang [48] found a relation between JIT implementation and MRP implementation, whereas Rodríguez-Méndez, et al. [56] associated JIT with SMED and maintenance systems. Similarly, to Cua, McKone and Schroeder [14], JIT goes hand in hand with quality systems and maintenance systems. Finally, Hou and Hu [6] developed a genetic algorithm to integrate Kanban with JIT, while Abdul-Nour, et al. [57] studied the JIT-Kanban relation and associated it with economic lot size. Following this discussion, the ninth hypothesis of this research is proposed as follows:

H9. *Production Tools and Techniques have a positive direct effect on Operational Benefits in the JIT implementation process.*

Figure 1 depicts the variables analyzed in this research along with their corresponding interrelations, illustrated as hypotheses. In the figure, variable *MAC* is the independent variable, whereas *OBE* is the dependent variable.

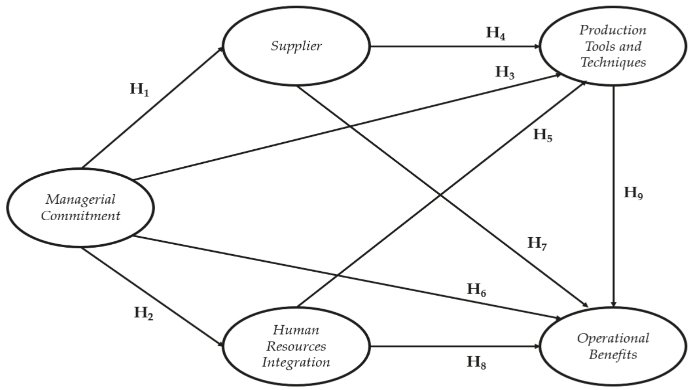

Figure 1. Proposed model.

3. Materials and Methods

The goal of this research is to relate human factor variables and JIT techniques with *OBE* through a structural equation model. To this end, we collected data from the manufacturing industry to determine the relationships between latent variables and test the model validity and reliability. This section discusses the materials and methods employed to reach our goal.

3.1. Questionnaire Design and Administration

A questionnaire is designed to study the latent variables proposed in Figure 1. To identify the items or observed variables that would allow us to assess each latent variable, a literature review is conducted. This stage represented the questionnaire's rational validation process. Then, the draft questionnaire is validated by scholars and regional industrial managers, who answered each question or item using a five-point Likert scale. The final survey was aimed at managers, production supervisors, and JIT implementation engineers. To select the sample, first a stratified sampling method was applied on potential participants who had at least one year of experience in JIT implementation. Then, the snowball sampling method was used when responders recommend other colleagues, increasing the sample's size. Please check the applied questionnaire, which appears as Supplementary Material 1.

3.2. Data Capture, Screening, and Descriptive Analysis

The software program SPSS 24® is used to capture the information collected via the questionnaires [58]. Then, then the following screening tasks are performed on the database to avoid biased results:

- Identify missing values: the identified missing values are replaced by the median value. However, questionnaires with more than 10% missing values are removed from the analysis.
- Identify outliers: the identified outliers are replaced by the median value, since they directly affect the parameter estimation process.

Finally, a descriptive analysis is performed for each latent variable, thereby obtaining a median value—as a measure of central tendency—and interquartile range value (i.e., the difference between first quartile and third quartile)—as a measure of data dispersion [58].

3.3. Data Validation

Before testing the model, six coefficients are estimated to validate the five latent variables depicted in Figure 1:

- R-Squared (R^2) and adjusted R-Squared (Adj. R^2) as indicators of parametric predictive validity. Values higher than 0.2 are necessary [59].
- Q-Squared (Q^2) as an indicator of non-parametric predictive validity. Values greater than 0 and similar to their corresponding R^2 values are necessary [60].
- Composite reliability index and Cronbach's alpha index as indicators of internal validity. Values higher than 0.7 are sought [61].
- Average Variance Extracted (AVE) as a measure of discriminant validity. Values higher than 0.5 are sought [62].
- Variance Inflation Factors (VIFs) as a measure of collinearity. Values lower than 3.3 are sought. However, the squared correlations between the latent variables is used for detecting multicollinearity and test discriminant validity, showing on diagonal the squared root of AVE [63].
- Also, factor cross loadings are analyzed to determine convergent validity of items into latent variables. Values higher than 0.5 are sought [64].

3.4. Model Evaluation

The model illustrated in Figure 1 is tested using the structural equations modeling (SEM) technique based on partial least squares (PLS) and integrated in WarpPLS 6® software program, which is recommended for ordinal, non-normal data and small samples [65], and similar research has been performed using these techniques, such as, for example, Díaz-Reza, et al. [66], who related the SMED stages to the benefits gained, and Boon Sin, et al. [67], who reported the relationship between knowledge management and six sigma success. The indices and parameters for model validation were obtained with a 95% confidence level. The following model fit and quality indices were estimated [68]:

- Average Path Coefficient (APC) and a p value lower than 0.05 is required.
- Average R-Squared (ARS) and Average Adjusted R-Squared (AARS) as indicators of predictive validity, and p values lower than 0.05 are required.
- Average block VIF (AVIF) and Average Full collinearity VIF (AFVIF) as a measure of multicollinearity. A value lower than 3.3 is required.
- Tenenhaus Goodness of Fit (GoF) Index to measure model fit. A value higher than 0.36 is necessary.

3.4.1. Direct Effects and Effect Sizes

In structural equation models, direct effects measure the relationship between two latent variables. They are usually depicted as arrows and help validate research hypotheses, such as those depicted in Figure 1. The magnitude of each effect is estimated using the beta (β) coefficient, which indicates in standard deviations how much a dependent latent variable varies as its corresponding independent latent variable increases or decreases by one unit. For all the effects, the corresponding confidence interval is estimated at 95%.

Finally, all the dependent latent variables are associated with an R^2 value as a measure of explained variance on it. The R2 coefficient indicates the percentage of variance in a dependent variable that can be explained by one or more independent variables. If two or more independent variables are responsible for the variability of a dependent latent variable, the R^2 value must be decomposed into effect sizes (ES).

3.4.2. Sum of Indirect Effects and Total Effects

The hypotheses depicted in Figure 1 represent direct effects; however, a relationship between two latent variables can also occur using one or more mediating variables. In this sense, indirect effects link two latent variables through two or more segments or model paths. This research only reports the sum of the indirect effects for each relationship with a 95% confidence interval. Finally, the total effects (i.e., sum of direct and indirect effects in a relationship between two latent variables) were also calculated, and each indirect and total effect value is associated with a p value—as an indicator of statistical significance—and an ES value.

3.4.3. Sensitivity Analysis

Managers really want to know what will happen if they have some situation, such as, for example, poor relationships with *SUP*, and how that will affect the possible benefits offered by JIT. To address this, a sensibility analysis is reported with different scenarios for the model's latent variables; since these are standardized values, the conditional probabilities can be estimated. For every research hypothesis proposed in Figure 1, the following aspects are estimated:

- The probability of a variable occurring on a lower or higher level independently; that is, $P(Z < -1)$ and $P(Z > 1)$, respectively.
- The probability of each variable occurring simultaneously in its multiple possible combinations. This probability is represented by *&*, and the combinations are: $P(Z_i > 1)$ and $P(Z_d > 1)$, $P(Z_i > 1)$ and $P(Z_d < -1)$, $P(Z_i < -1)$ and $P(Z_d > 1)$, $P(Z_i < -1)$ and $P(Z_d < -1)$.
- The probability of the occurrence of a dependent latent variable on a certain level with respect to the variability of an independent latent variable. This is a conditional probability expressed using the word *If*. For each research hypothesis, four possible combinations were found: $P(Z_i > 1/Z_d > 1)$, $P(Z_i > 1/Z_d < -1)$, $P(Z_i < -1/Z_d > 1)$ and $P(Z_i < -1/Z_d < -1)$.

The sensitivity analysis makes it possible to further explore the risks/benefits of having either low or high levels in the latent variables. Namely, $P(Z_i)$ represents the probability of an independent variable in a given level, whereas $P(Z_d)$ stands for the probability of a dependent variable. Finally, in sensitivity analyses, the plus (+) and minus symbols (−) are used to indicate high and low values in the latent variables, respectively. For instance, *MAC+* indicates a high level of *MAC*, whereas *SUP−* indicates a low level in *SUP*.

4. Results

This section comprises three subsections that respectively discuss the results obtained from the sample's descriptive analysis, the item's descriptive analysis, and the model's assessment.

4.1. Sample Characterization

The survey was administered for three months (June–August 2019) in Mexican manufacturing companies located in Ciudad Juarez, Chihuahua. In total, 352 valid questionnaires were collected, 104 of which had been answered by female and 248 by male participants. As for the job positions, the sample was formed of 178 production system engineers, 153 production supervisors, and 21 managers. Table 2 summarizes the results regarding the surveyed industries and the sample's length of field experience. As can be observed, the automotive, medical, and electrical industries are the most prominent.

Table 2. Surveyed industries and length of experience (years).

Industry	Years of Experience				Total
	1–2	2–5	5–10	>10	
Automotive	41	72	24	21	158
Medical	17	42	19	8	86
Electrical	7	25	12	11	55
Electronics	5	19	9	18	51
Aerospace	1	1	0	0	2
Total	71	159	64	45	352

4.2. Descriptive Analysis and Validation of Items

Table 3, below, summarizes the results from the descriptive analysis of the items included in the latent variables. The items appear ranked in descending order according to their median values. In this sense, it is found that in terms of *MAC*, interdepartmental communication and coordination is the most important aspect, along with a culture of compliance. As for *HRI*, the analysis revealed that both employee training/education and job rotation are the most valuable. These aspects help manufacturing companies have multifunctional employees, which consequently can improve the material flow. With respect to *TTP*, Poka-joke systems are the most important, since they prevent errors from being propagated along the production system. Moreover, Poka-joke systems help to standardize production processes. As regards *SUP*, findings reveal that quality certificates and long-term contracts are essential, and thus appear as indicators of *Supplier* reliability. Finally, in terms of *OBE*, JIT reduces final product delivery times (a basic quality principle), waste, and inventory levels of both raw materials and work in progress.

Table 3. Item descriptive analysis and convergent validity test.

Latent Variable/Item	Median	IQR
MAC1	4.20	1.584
MAC2	4.11	1.58
MAC3	3.94	1.587
MAC4	3.71	1.608
HRI1	3.85	1.647
HRI2	3.73	1.754
HRI4	3.67	1.71
HRI6	3.43	1.837
HRI3	3.39	1.9
HRI5	3.18	1.917
TTP4	4.09	1.578
TTP8	4.08	1.563
TTP3	4.05	1.775
TTP5	3.89	1.651
TTP7	3.88	1.476
TTP1	3.85	1.619
TTP6	3.62	1.626
TTP2	3.4	1.928
SUP4	4.12	1.59
SUP3	3.93	1.569
SUP2	3.84	1.587
SUP1	3.66	1.832
SUP5	3.55	1.741
OBE5	3.91	1.513
OBE7	3.86	1.675
OBE1	3.77	1.537
OBE2	3.75	1.516
OBE6	3.73	1.67
OBE3	3.71	1.648
OBE4	3.68	1.581

Table 4 lists the coefficients estimated to test the validity of the latent variables. According to these results, all the latent variables have enough parametric and non-parametric validity, since all the R^2, adjusted R^2, and Q^2 values are higher than 0.2. Likewise, no internal collinearity problems are found in the latent variables, since all the VIF values are lower than 3.3. Finally, the Cronbach's alpha and composite reliability values indicate that the five latent variables have enough internal validity (i.e., the values are higher than 0.7).

Table 5 indicates the cross loadings for items in latent variables, indicating that there is an adequate discriminant validity because all they are higher than 0.5, the minimum cut-off admissible in this research.

Table 4. Latent variable coefficients.

Index	Latent Variable				
	HRI	*MAC*	*SUP*	*TTP*	*OBE*
R^2	0.251		0.265	0.626	0.547
Adjusted R^2	0.249		0.263	0.623	0.542
Composite reliability	0.864	0.872	0.862	0.896	0.923
Cronbach's alpha	0.811	0.804	0.799	0.867	0.903
Average variance extracted	0.516	0.631	0.557	0.519	0.634
Variance inflation factor	1.664	1.636	2.164	3.153	2.169
Q^2	0.251		0.266	0.625	0.547

Table 5 indicates the cross loadings for items in latent variables, indicating that there is an adequate discriminant validity. Observe that italic cross loading values, associated to every latent variable, are the highest in their row. Finally, Table 6 indicates the correlation among latent variables and values indicates absence of multicollinearity and adequate discriminant validity. Observe that bold values, associated to latent variable, are the highest in their column and row. Please check Supplementary Material 2 for *t* values associated with cross loadings and their confidence interval.

Table 5. Cross loadings.

Ítems	Latent Variables				
	HRI	*MAC*	*SUP*	*TTP*	*OBE*
HRI1	*0.66*	0.22	−0.31	0.315	−0.016
HRI2	*0.659*	−0.113	−0.042	0.234	0.051
HRI3	*0.765*	−0.05	0.077	−0.188	−0.065
HRI4	*0.731*	−0.064	−0.123	−0.009	0.054
HRI5	*0.645*	0.194	0.126	−0.103	0.016
HRI6	*0.69*	−0.178	0.254	−0.097	−0.024
MAC1	−0.115	*0.714*	−0.039	0.078	−0.032
MAC2	0.021	*0.737*	0.13	−0.237	−0.033
MAC3	0.165	*0.688*	−0.031	−0.106	0.032
MAC4	−0.041	*0.625*	−0.089	0.333	0.058
SUP1	0.026	−0.103	*0.613*	0.237	0.139
SUP2	−0.011	−0.086	*0.678*	0.094	−0.106
SUP3	0.005	0.045	*0.687*	−0.116	−0.091
SUP4	−0.121	0.169	*0.644*	0.17	−0.108
SUP5	0.111	−0.031	*0.653*	−0.385	0.241
TTP1	0.191	−0.111	−0.098	*0.613*	−0.076
TTP2	0.226	−0.305	−0.018	*0.624*	−0.001
TTP3	−0.075	−0.188	−0.036	*0.659*	−0.083
TTP4	−0.062	0.194	−0.148	*0.599*	0.035
TTP5	−0.163	−0.042	0.015	*0.618*	0.121
TTP6	0.033	0.268	−0.109	*0.571*	0.356
TTP7	−0.02	0.174	0.178	*0.592*	−0.02
TTP8	−0.089	0.185	0.197	*0.605*	−0.208
OBE1	−0.011	0.098	−0.153	0.022	*0.659*
OBE2	−0.034	0	0.065	−0.058	*0.652*
OBE3	−0.065	0.086	−0.154	0.11	*0.654*
OBE4	0.087	−0.166	0.152	−0.071	*0.646*
OBE5	−0.147	0.091	0.002	0.177	*0.631*
OBE6	0.059	−0.097	0.042	−0.067	*0.658*
OBE7	0.135	−0.044	0.105	−0.125	*0.636*

Table 6. Squared correlations between latent variables (with AVE on the diagonal).

Latent Variables	Latent Variables				
	HRI	*MAC*	*SUP*	*TTP*	*OBE*
HRI	***0.718***	0.499	0.468	0.592	0.508
MAC	0.499	***0.794***	0.506	0.557	0.518
SUP	0.468	0.506	***0.746***	0.518	0.584
TTP	0.592	0.557	0.518	***0.72***	0.701
OBE	0.508	0.518	0.584	0.701	***0.796***

4.3. Model Testing

Figure 2 depicts the structural equation model already evaluated. Every relationship among the latent variables is associated with a β value as a measure of dependency and a *p*-value as an indicator of statistical significance. Since all the *p*-values are lower than 0.05, it is concluded that all the direct effects proposed by the hypotheses are statistically significant at a 95% confidence level. For instance, as regards the first hypothesis (H_1), there is enough statistical evidence to confirm that *MAC* has a positive direct effect on *SUP* in a JIT implementation process, since when the former increases by one standard deviation, the latter increases by 0.515 standard deviations. Similar interpretations can be formulated for the remaining hypotheses. Please check Supplementary Material 2 for detailed *t* values associated with β values and their confidence intervals.

Table 7 summarizes the conclusions about the hypotheses according to the *p*-values associated with β.

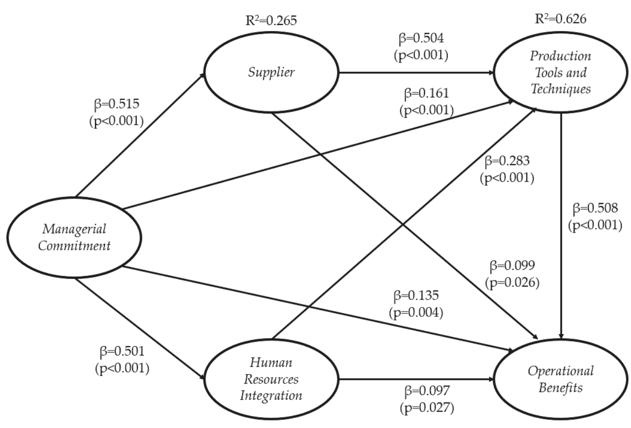

Figure 2. Evaluated model (validation of hypotheses).

Table 7. Hypothesis validation results.

H_i	Independent Variable	Dependent Variable	β Value (*p*-Value)	Conclusion
H1	*MAC*	*SUP*	0.515 ($p < 0.001$)	Accepted
H2	*MAC*	*HRI*	0.501 ($p < 0.001$)	Accepted
H3	*MAC*	*TTP*	0.161 ($p < 0.001$)	Accepted
H4	*SUP*	*TTP*	0.504 ($p < 0.001$)	Accepted
H5	*HRI*	*TTP*	0.283 ($p < 0.001$)	Accepted
H6	*MAC*	*OBE*	0.135 ($p = 0.004$)	Accepted
H7	*SUP*	*OBE*	0.099 ($p = 0.026$)	Accepted
H8	*HRI*	*OBE*	0.097 ($p = 0.027$)	Accepted
H9	*TTP*	*OBE*	0.508 ($p < 0.001$)	Accepted

Table 8 summarizes the results after decomposing the R^2 value in every dependent latent variable. The goal at this stage is to determine which independent variable is more important to a dependent variable to which it is related. In this sense, *OBE* (dependent latent variable) is 54.7% explained by four independent latent variables, among which *TTP* is the most important because its contribution to the R^2 value is higher (ES = 0.365 or 36.5%). In turn, the most important variable to explain *TTP* is *SUP* (ES = 0.365 or 36.5%).

Table 8. Effect sizes (ES) for direct effects.

Dependent Variable	Independent Variable				R^2
	HRI	*MAC*	*SUP*	*TTP*	
HRI		0.251			0.251
SUP		0.265			0.265
TTP	0.169	0.092	0.365		0.626
OBE	0.051	0.072	0.059	0.365	0.547

Table 9 lists both the sum of indirect effects and the total effects found in the relationships. Every effect is associated with a β value, a *p*-value as the indicator of statistical significance, and an ES value. Such results help to understand the relationships between two variables that, at first glance, seemed to have little or no significant connection. For instance, the direct effect of *MAC* on *TTP* is only 0.161 units, yet the sum of their indirect effects is equal to 0.401 units. In the end, the relationship between *MAC* and *TTP* has the highest total effects—i.e., 0.562 units. A similar phenomenon occurs in the relationship between *MAC* and *OBE*, where the indirect effect is higher than the direct effect.

Table 9. Sum of indirect effects and total effects.

Sum of Indirect Effects				
Dependent Variable	**Independent Variable**			
	HRI	*MAC*	*SUP*	*TTP*
TTP		0.401($p < 0.001$) ES = 0.229		
OBE	0.144 ($p < 0.001$) ES = 0.074	0.386 ($p < 0.001$) ES = 0.207	0.256 ($p < 0.001$) ES = 0.151	
Total Effect				
HRI		0.501 ($p < 0.001$) ES = 0.251		
SUP		0.515 ($p < 0.001$) ES = 0.265		
TTP	0.283 ($p < 0.001$) ES = 0.169	0.562 ($p < 0.001$) ES = 0.321	0.504 ($p < 0.001$) ES = 0.365	
OBE	0.242 ($p < 0.001$) ES = 0.125	0.521 ($p < 0.001$) ES = 0.279	0.355 ($p < 0.001$) ES = 0.210	0.508 ($p < 0.001$) ES = 0.365

Table 10 introduces the findings from the sensitivity analysis. The table indicates the probability of each latent variable to lie at a high or low level independently, conjointly, or conditionally. For instance, *MAC* is more likely to lie at a high level (*MAC*+) independently than to lie at a low level (*MAC*+). Consequently, the likelihood of *Supplier* levels being high (*SUP*+) is greater if *MAC* levels are high (*MAC*+). Conversely, low *MAC* levels (*MAC*−) imply greater risks (i.e., 0.397) of having low levels in *SUP* (*SUP*−). In conclusion, if there is little likelihood of having high *Supplier* levels due to low levels in *MAC*, top managers must be particularly careful with and attentive to the company's relationship with its *SUP* in the JIT implementation process.

Table 10. Sensitivity analysis results.

				Independent Latent Variables							
				MAC		*SUP*		*HRI*		*TTP*	
				+	−	+	−	+	−	+	−
				0.161	**0.169**	**0.159**	**0.153**	**0.175**	**0.159**	**0.169**	**0.156**
Dependent latent variables	*SUP*	+	0.159	&0.056 *If* 0.350	&0.008 *If* 0.048						
		−	0.153	&0.005 *If* 0.033	&0.067 *If* 0.397						
	HRI	+	0.175	&0.065 *If* 0.400	&0.005 *If* 0.032	&0.062 *If* 0.390	&0.000 *If* 0.000				
		−	0.159	&0.013 *If* 0.083	&0.067 *If* 0.397	&0.013 *If* 0.085	&0.059 *If* 0.386				
	TTP	+	0.169	&0.067 *If* 0.417	&0.005 *If* 0.032	&0.081 *If* 0.508	&0.000 *If* 0.000	&0.086 *If* 0.492	&0.005 *If* 0.034		
		−	0.156	&0.011 *If* 0.067	&0.073 *If* 0.429	&0.000 *If* 0.000	&0.097 *If* 0.630	&0.003 *If* 0.015	&0.081 *If* 0.508		
	OBE	+	0.148	&0.046 *If* 0.283	&0.008 *If* 0.048	&0.062 *If* 0.390	&0.003 *If* 0.018	&0.059 *If* 0.338	&0.008 *If* 0.051	&0.086 *If* 0.508	&0.003 *If* 0.017
		−	0.140	&0.008 *If* 0.050	&0.056 *If* 0.333	&0.003 *If* 0.017	&0.067 *If* 0.439	&0.008 *If* 0.046	&0.067 *If* 0.424	&0.000 *If* 0.000	&0.089 *If* 0.569

5. Discussion: Industrial and Managerial Implications

This research integrates five latent variables in a structural equation model to assess their interrelations and effects in the JIT implementation process. Our research findings and their implications can be discussed as follows:

- *MAC* is the key to JIT implementation in production systems [48], since it has the highest positive direct effects on the remaining variables. Because managers make the final decisions, they have to be the most involved in the JIT implementation process, especially in aspects that involve *HRI* and a company's relationship with its *SUP*.
- *MAC* has a positive direct impact on *TTP*. Considering that managers ultimately decide what *TTP* are implemented in a production system, the value of the direct effect is relatively low (β = 0.161). However, after analyzing the indirect effects (β = 0.401) that occur thanks to mediating variables *SUP* and *HRI*, we found that the relationship between *MAC* and *TTP* is much more important, since the total effects are β = 0.562. Such results imply that managers need support from both operators and *SUP* to implement *TTP*, who can train operators in the use of specific production techniques. This claim is consistent with that of Shnaiderman and Ben-Baruch [35].
- The direct effect of *MAC* on *OBE* is only β = 0.135; however, after analyzing the indirect effects that occur thanks to *SUP*, *HRI*, and *TTP* (β = 0.386), we found that the total effects in this relationship are β = 0.521. These results imply once more that JIT benefits can be obtained only if managers plan the JIT implementation process carefully, by properly integrating human resources (including *SUP*) and production machinery, techniques, and methodologies [9].
- *Human Resources* that are well integrated in production tools, namely lean manufacturing tools, are a key element in obtaining the desired *OBE* [68]. In this research, we found a relatively low positive direct effect from *HRI* on *OBE* (i.e., β = 0.097). However, the relationship is much more important when taking into account the indirect effects that occur through *TTP* (β = 0.144); that is, the total effects in the relationship between *HRI* and *OBE* report β = 0.242. These results demonstrate that operator knowledge, experience, and skills must be applied in *TTP*. Consequently, managers must promote collaborative work environments and the development of multifunctional skills, which would contribute to a correct material flow.
- *SUP* may be external entities, yet they do have an impact on the *OBE* that companies gain by implementing a JIT system. *SUP* are important since they supply manufacturers with raw materials, machinery, and equipment. The direct relationship between *SUP* and *OBE* has a low but still significant value of β = 0.099; however, the indirect effects caused by *Production Tools and*

Technologies have a value of β = 0.256. In total, the relationship has a value of β = 0.355, which reveals that managers must be attentive to the technological innovations that *SUP* can offer them to improve the production flow along the system. This is where improvements can be made by proposing new production techniques.

- Direct and indirect effects are interesting, yet it is also important to analyze the performance of the latent variables under certain conditions. In this sense, the implications of the sensitivity analysis performed on the latent variables (see Table 8) can be discussed as follows:
- High levels of *MAC* are essential for the performance of all the other variables. *MAC*+ increases the likelihood of *SUP*+ by 0.350, that of HRI+ by 0.400, the likelihood of TTP+ by 0.470, and that of OBE+ by 0.283. Conversely, low *MAC* levels (*MAC*−) increase the risks of both *SUP*− and *HRI*− by 0.397, those of TTP− by 0.429, and the risks of OBE− by 0.333.
- *SUP* are external entities; however, as the first supply chain system component, they can facilitate the JIT implementation process. High levels in *SUP* (i.e., *SUP*+) increase the likelihood of *HRI*+ by 0.390 and that of *TTP*+ by 0.508, which is a value much higher than that of *MAC*+. Similarly, *SUP*+ increases the likelihood of OBE+ by 0.390. On the other hand, low *Supplier* levels (i.e., *SUP*−) imply risks in the other variables. Namely, it is impossible for production systems to rely on well-implemented *TTP*, since the value of *TTP*+ is 0, whereas the value of *TTP*− is 0.630. Likewise, *SUP*− does not guarantee *OBE*+, as the likelihood value is only 0.003, while the risks of *OBE*− increase by 0.439. Such results imply that *SUP* are the supporting base of the JIT implementation process in production systems, which is consistent with what authors Shnaiderman and Ben-Baruch [35] claim.
- Appropriate *MAC* and good relationships with *SUP* do not guarantee the success of JIT on their own. *HRI* is equally important. According to our analysis, *HRI*+ increases the likelihood of *TTP*+ by 0.492 and that of *OBE*+ by 0.338. However, *HRI*- guarantees neither *TTP*+ nor *OBE*+, since the likelihood values are 0.005 and 0.008, respectively. Finally, *HRI*− increases the risks of *TTP*− by 0.508 and those of *OBE*− by 0.424. These results demonstrate that human experience and skills are necessary to successfully implement *Production Tools and Technologies* in production systems, which is consistent with what authors García-Alcaraz, et al. [10] argue.
- Finally, we found that *TTP*+ guarantees *OBE*+ (0.508) and is never associated with *OBE*− (0.000). Nevertheless, *TTP*− cannot guarantee *OBE*+ and increases the risks of *OBE*− by 0.659. In conclusion, JIT must not be isolated from the *Production Tools and Technologies* already implemented in a production system, such as MRP [45,48], TQM y TPM [14,21], and SMED [69], to name but a few.

6. Conclusions, Limitations and Future Research

JIT is a lean manufacturing tool that offers attractive benefits to production systems when it is well implemented. A solid JIT system requires hard work to associate the obtained benefits and generate tangible metrics. Similarly, as a philosophy, JIT depends on both internal human factors (managers, operators) and external human factors (*SUP*) and managers must pay attention to their human resources satisfaction and knowledge. Quantitative findings in this research led to the conclusion that human research is an important factor for JIT implementation success, and it is not an isolated technique, as it must be integrated with all of the other techniques that are already implemented in production systems that support materials flow. For example, Hou and Hu [6] integrated Kanban with JIT using genetic algorithms, and Al-Tahat and Mukattash [46] proposed a new production design for integrating these Techniques.

In relation to the sensitivity analysis performed with conditional probabilities, the following quick conclusions could be obtained:

- High levels on *MAC* provide high levels on *SUP*, *HRI*, *TTP*, and guarantee *OBE*; however, low levels on *MAC* propitiate risks of obtaining low levels for these variables.

- High *SUP* levels promote high levels of *HRI*, *TTP* and *OBE*. In contrast, low *SUP* levels represent a risk for these variables and the entire JIT implementation process.
- High levels on *HRI* facilitate the attainment of high levels of *TTP* and *OBE*, and conversely, low levels of *HRI* pose a risk, as human resources are responsible for implementing JIT.
- Finally, high levels on *TTP* guarantee high levels on *OBE* since they support the JIT philosophy. In the same way, low *TTP* levels are a risk to the JIT implementation process.

However, this research reports the results from a structural equation model that integrates only four independent latent variables or critical success factors associated with JIT and a dependent variable associated with operating benefits, and there are many other variables and benefits associated with JIT. This indicates that the current model is not complete, and that other analyses are required to generate integrative models with greater explanatory power, which can be easily observed in the R^2 values of the dependent variables. They are not totally explained, since they are values lower than one, which can be considered a limitation of this research.

In the same way, this study focuses on the maquiladora industry, which is predominant in the northern region of Mexico and is represented by the automotive and electronics industry sectors; so these results can only be applied to those specific sectors. The above limitations suggest that the following future research should be proposed:

- Apply the survey used in other sectors in order to find differences and effectiveness of the model, since JIT is a tool that can easily be applied in different types of industries, such as hospitality and food services, where customer satisfaction is strongly related to timely delivery.
- Generate an integral and holistic model that makes it possible to incorporate more latent variables and, in this way, increase its explanatory power and the R^2 values for the dependent variables.

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A Proposed Index of the Implementation and Maturity of Circular Economy Practices—The Case of the Pulp and Paper Industries of Portugal and Spain

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Abstract: High industrial development, new consumption habits, and population growth have led to a discussion, in the various sectors of society, about resource scarcity, pollutant emissions, and waste generation. As a result, and in opposition to the linear economic model in which products are eliminated after production and consumption, a new business model emerged, called the "The Circular Economy". This model is based on reuse, recovery, recycling, and repairing during the design and use cycle of a product. This research intends to make a study of the circular economy in the pulp and paper industries of Portugal and Spain. This sector was chosen because, in addition to representing about 2.5% of Portugal's industrial production, it has made significant efforts to promote environmentally sustainable development. Therefore, this research intends to present the situation of the pulp and paper sector within the circular economy, making an Iberian comparison between the years 2011 and 2015. This comparison is made through the development of a comparative index based on the results of some environmental indicators. According to the research carried out, the pulp and paper sector in Portugal was about 26% higher in the implementation of the circular economy than the same sector in Spain in 2015, with the peculiarity that this difference has been decreasing in the last five years.

Keywords: circular economy; pulp and paper industry; comparative index; cross-country analysis

1. Introduction

High industrial development, new consumption habits associated with population growth, and the consequent growth of the industrial sector have led to a discussion [1] in several segments of society. This discussion addresses topics concerning resource scarcity, an increase in greenhouse gas emissions, and waste generation. Despite the efforts to promote recycling and the measures aimed at reducing the need for resource extraction, consumer goods continue to follow a linear logic: They are not reused and are often disposed in landfills after usage. These factors have led to increased resource consumption, greenhouse gas emissions, liquid effluent rejection, and overuse of space to end-of-life products. In this context, the concept of the "circular economy" emerged [2–4].

The circular economy is a model that aims to rethink the economic practices of today's society [5]. Based on the principle of "closing the life cycle" of products, it aims to ensure resource efficiency and minimize the amount of unwanted emissions and waste [6]. It also promotes relationships between companies so that one can use the waste of another as a by-product in its production process [7].

In order to promote the circular economy, the European Union, in its communication *Closing the loop—An EU action plan for the Circular Economy*, has precise strategies and policies, both in the area of consumption and in residual management, highlighting the existing possibility of using waste as raw material in the same or in other production processes [8]. In the context of these policies, the consumption of raw materials and the production of waste have been gaining importance in the last decades, even being one of the priority areas of the European Union [9]. Portugal, within the European Union and its policies, has developed a plan—the National Waste Management Plan (NWMP)—implemented by the Portuguese Environmental Agency (APA). In this sense, since the main objective of the NWMP is environmentally sustainable development, it becomes important to characterize and study the circular economy implementation in the Portuguese industrial area, and compare it with similar industries in European countries. This is the focus of the present research. The Portuguese pulp and paper sector, which also comprises the cardboard industry, accounts for around 2.5% of the national industrial production, 4.6% of tradable goods exportation with high national added value, and 1.2% of employment in the Portuguese economy [10]. Therefore, this is the research field that this paper intends to focus on.

The main objective of this research is to develop a comparative index to support a cross-country analysis of the circular economy implementation in the pulp and paper industries of Portugal and Spain. To this end, the pulp and paper industries' environmental and production variables will be used to evaluate the industries, considering several categories. Based on the conclusions drawn from the comparative index value, this paper aims to conclude about the implementation of the circular economy in both countries.

This article follows the following structure: The first introductory section, where the aim of the study is presented, contains relevant information about the topic under study. In Section 2, the state of the art about the circular economy concept, practices for its implementation, and indicators used in the evaluation of the circular economy concept are addressed. Next, in Section 3, the pulp and paper industries of Portugal and Spain are presented. Furthermore, the development of a comparative indicator, as well as the data collection, is presented in this section. The results related to the environmental indicators are presented in Section 4. In this section, the comparative analysis method is also used to compare the implementation of the circular economy in the sectors in two groups of Pulp and Paper companies. Simultaneously, an analysis is performed on the results obtained. Section 5 presents general conclusions about the research.

2. State of the Art

2.1. The History and the Concept of Circular Economy

Currently, the demand for products and services, and the need for resources to produce them, has increased to levels never verified before. This scenario contributes to the growth of waste production and environmental pollution [3]. This growth causes an increase in global temperature due to the emission of gases into the atmosphere [11]. This context is also conducive to economic uncertainties [12], and since the use of natural resources for production processes is always necessary, they remain limited [3].

The concept of circular economy—which has been defined and improved by different schools of thought—is not new and has already been developed in many countries over time. It has several origins and cannot be associated with a single date or author [13]. It began with practical applications for industrial processes that were developed in the late 1970s as a result of studies led by a large number of academics, thinkers, and entrepreneurs [6].

In 1982, Stahel, an architect and economist who founded the "*cradle-to-cradle*" (C2C) and founded the *Product Life Institute* in Geneva in 1970, wrote a scientific paper entitled "*The product life factor*", which addresses the product life cycle and its extent—the "performance economy"—that is a crucial point in creating a sustainable society, based on resources that are finite on the planet. German chemist Michael Braungart, along with American architect Bill McDonough, continued to develop the concept and process of certification C2C, the precursor of the circular economy [6]. This concept is based on three fundamental principles: Elimination of the waste concept, use of renewable energies (mainly solar energy), and water use management that promotes healthy ecosystems and respects local impacts [6].

In contrast to the linear economy, which is a business model characterized by "extraction–use–deposition" [6], the circular economy has gained new importance [14]. The basis of the concept of circular economy is the creation of a green economy, which is in accordance with the principle of the "3 R's": Reduce, which supposes to reduce the number of substances, both in the extraction (as in the production) and the consumption; reuse; and recycle [15]. Although it includes the concept of the 3 R's, the circular economy aims to create other conditions so that resources and energy flow in a circular way, maximizing the efficient use of natural resources and minimizing the deposition of waste in landfills. An example is *eco-design*, in which products are designed so that they can be reused, thus reducing the need to extract new natural resources at the beginning of the production process [1].

2.2. Practices for Implementation of Circular Economy—Applications in Industry

In economic systems, using the circular economy model would guarantee well-established competition [16], bringing benefits at the micro and macroeconomic levels, stimulating the growth of new business models and, consequently, job creation [6].

For the implementation of circular economy, efforts are required at three different levels: The micro (single entity), meso (association of entities), and macro (city, region, and country) levels [17,18]. It can also be applied in three main areas: Production, consumption, and waste management. It is worthwhile to say that it is very present in the area of industrial production.

The implementation of the circular economy in industrial production is inherently related to the concept of "industrial ecology". In contrast to traditional industry, industrial ecology relies on the concepts of "eco-efficiency" in the industry and "industrial symbiosis". Industrial symbiosis is a concept that promotes the business model in circles, based on "extraction–consumption–raw material" [19,20]. Industrial symbiosis creates closed-loop processes in which waste is seen as an input byproduct and not as an undesirable residue [20].

Industrial ecology seeks to "imitate" nature and focuses on one of the basic principles of circular economics, which is bio-mimetics. Bio-mimetics consists of the creation of cycles of materials and energy, with the principle of the use of renewable resources and energy [21]. In this way, the concepts of circular economy and "industrial ecology" are strongly related [19].

2.2.1. Eco-Efficiency

According to the World Business Council for Sustainable Development (WBCSD), eco-efficiency is "a management philosophy that encourages the business world to seek environmental improvements that enhance, in parallel, economic benefits. It focuses on business opportunities and enables companies to become more environmentally responsible and more profitable. It encourages innovation and, therefore, growth and competitiveness" [22].

Although it is not directly related to the fundamental concept of circular economy, eco-efficiency draws attention to multiple objectives of the circular economy, such as reducing resource consumption, reducing energy consumption, reducing emissions of polluting gases and effluents, and reducing waste production. Eco-efficiency is a great step towards the application of industrial ecology and, consequently, to circular economy [23].

There are several calculation methods for the quantification of eco-efficiency [24]. However, in this research, and since economic variables are the predominant form of environmental data exposure, eco-efficiency can be calculated according to a company's sustainability reports, by the ratio of an environmental variable to an economic variable [25,26]. Therefore, Equation (1) is used to calculate the eco-efficiency indicators in this research.

$$Quantification\,of\ Eco\text{-}efficiency = \frac{Environmental\ Variable}{Economic\ Variable\,(Production)} \quad (1)$$

2.2.2. Industrial Symbiosis

With the emergence of industrial ecology, the study and promotion of industrial symbiosis have been developed [27]. The concept of industrial symbiosis is based on the relationships of biology. In this context, the term "symbiosis" refers to the exchange of materials and energy in a collectively beneficial way between two species. Within this line, the term "industrial symbiosis" aims at the exchange needs between industries, with the objective of achieving competitive and environmental advantages. Making this analogy, three types of transactions may occur in an industrial symbiosis relationship [28]:

- Sharing of infrastructures;
- Sharing common service needs;
- By-product exchanges, where one industry uses the waste of another company as raw material.

Equation (2) was proposed to evaluate the implementation of industrial symbiosis (*IIS*) [29].

$$ISS = \frac{RIC}{1 + OIQ} \quad (2)$$

RIC—Rolling impact quantity (e.g., amount of waste exchanged in symbiosis);
OIQ—Output impact quantity (amount of impact that is not exchanged in symbiosis).

For the calculation of rolling impact quantity and output impact quantity an evaluation of four criteria is proposed, composed by legislation, class, use/treatment, and destination of the waste [29]. This evaluation is done following a scale (1, 3, or 5), and the evaluator is invited to assign a weight in each criterion (from 0 to 1), according to the importance given by it.

2.3. Sustainability Indicators in the Evaluation of the Circular Economy

To evaluate the successful implementation of industrial ecology, and consequently, of the circular economy, a system of indicators becomes necessary [30]. These provide guidelines for decision-making and allow us to evaluate the effectiveness of the policies implemented in an entity [18,31,32]. There are already many metrics to study how the circular economy is being implemented and developed. Iacovidou et al. [31] propose four types of metrics: Environmental, economic, social, and technical metrics. Elia et al. [30] consider four categories: Material flow, energy flow, land use and consumption, and other life cycle-based parameters.

Su et al. (2013) [32] disclose two evaluation indicator systems for the circular economy offered by Chinese governmental agencies (Ministry of Environmental Protection and the National Development and Reform Commission). The following dimensions are considered: Resource output rate, resource consumption rate, integrated resource utilization, reduction rate in waste discharge, material reducing and recycling, economic development, pollution control, and administration and management. These dimensions include indicators related to the eco-efficiency assessment, and reuse and industrial symbiosis indicators:

- Eco-efficiency indicators: These indicators are production-based and are measured by the ratio of an input or output to the production of a given industry. Examples include: "Energy consumption per unit of production in the key industrial sector" and "Water consumption per unit of production value".
- Reuse and industrial symbiosis indicators: The reuse indicators are relevant because the better the performance, the less the extraction and use of new fresh inputs. Examples include: "Reuse ratio of industrial water" and "Recycling rate of industrial waste water".

Since this research is focused on the pulp and paper sector, in this paper we chose the environmental metrics to understand the environmental benefits and impacts of adopting the circular economy model. The environmental variable can be composed by inputs, which are the resources used in the production process, or by outputs, which are the "harmful consequences" that the same process causes in the environment. Environmental metrics can be analyzed by different perspectives. One of the most widely known and used metrics in environmental assessment is related to greenhouse gas emissions (CO_2, CH_4, N_2O, etc.). In addition, for assessing the environmental impact of various pollutants, there is a combined single metric called "pollutant emissions metric". The resource depletion metric includes the consumption of resources, such as primary energy consumption, specific energy consumption, and renewable energy generation, among others. However, the depletion of resources other than energy-based ones is also very important to analyze, such as: Water consumption or water lost through waste treatment, or disposal or specific material consumption. Non-energy raw materials are essential inputs to all industries. The amount of raw materials used to produce a product is of growing importance due to pressures related to their future availability [31].

3. Materials and Methods

3.1. The Pulp and Paper Industry in Portugal

The group of entities related to the production of pulp for paper and different types of paper is called the "paper industry" or "pulp and paper" sector. This activity extends to almost the entire life cycle of paper products, from the production of raw materials (forest production) to the treatment of end-of-life products, through the recycling or energy recovery of waste.

CELPA—Associação da Indústria Papeleira—represents the largest private owners and managers of the Portuguese forest, and the producers of 100% of the national production of virgin fiber pulp and 90% of the national production of paper and paperboard (CELPA, 2015). In national terms, CELPA members export to more than 140 countries, representing 4.6% of the total Portuguese exports of goods.

In addition to the theme of waste being fundamental to the application of the concept of circular economy, it is a cross-cutting theme that affects all industrial sectors, and the paper industry is no exception. Increasingly, there is an attempt to adopt a sustainable and balanced waste management, opting for the principles of waste minimization, creating good conditions for their selective collection, and always favoring the techniques of valorization to avoid landfill and other disposal methods, in order to protect the various natural resources. The successive improvement in the environmental performance of the paper sector is due to an intense investment program, started more than 20 years ago as a result of the environmental protection policy of this sector.

The production of solid waste, resulting from the industrial processes, is directly related to the production pattern of pulp and paper. Furthermore, other types of waste are produced, such as those resulting from the demolition and construction of buildings which, due to their occasional nature, have significant annual variations. These residues can be processual and non-processual. Processual waste results directly from the production of pulp and paper, and is considered specific to this activity. It is important to note that all the process waste that is produced in the paper industry is considered to be non-hazardous.

Waste is treated in different ways and can be disposed of or valorized. However, for waste to be valorized by other industries, it is necessary to classify these substances as a by-product. "By-product" means substances or objects that result from a production process in which the main objective is not its production (production residue). Those substances or objects can be directly used, without being processed (other than the normal industrial practice), in other applications and industries [33].

The associated companies of CELPA have worked, at technical and scientific levels, in the identification and development of solutions to promote the classification of processual residues as by-products for their use as raw materials in other production processes. The use of residues as by-products from the pulp and paper industry is the subject of rigorous studies and laboratory tests to demonstrate that they can be used in other products/markets.

To develop the present research, data was collected from primary sources through unstructured interviews with members of CELPA, with the purpose of knowing the characteristics of the pulp and paper industry. Additionally, interviews were done with two experts from CELPA in order to select the indicators and validate the results. Secondary data was collected from the statistical bulletin of ASPAPEL—*Asociacón Española de fabricantes de pasta, papel y carton* [34] —for the calculation of the indicators that characterize the circular economy in Spain. These data can be accessed through its website. For Portugal, the data used was taken and made available by CELPA and its statistical bulletin. The data available is relevant to the period between 2011 and 2015 and, as such, the calculation of indicators is relative to this period.

3.2. Comparative Indicator Developement

To develop a comparative index to assess the circular economy implementation in the pulp and paper industry, the following steps were made:

- Step 1—Selection of eco-efficiency, and reuse and industrial symbiosis indicators. To assure that the indicators selected were related with the pulp and paper industry, the dimensions and environmental indicators proposed by Su et al. [32] were analyzed and discussed with experts from CELPA. Then, the availability or not of data for a particular indicator was considered to select the final set of indicators.
- Step 2—Computing the indicator values. Secondary data was used to compute the indicators. As the indicators had different units, subsequently, it became necessary to normalize them, that is, to size all categories of indicators so that their values were between 0 and 1. Standardization was achieved by grouping the results of the same category indicators', and each result was divided by the highest value of the indicator of the same category. The normalized indicator of value 1 represent the worst result, and value 0 represent the best value.
- Step 3—Computing the comparative index. The comparative index is a function of all the indicators selected in step 1. To combine the different indicator's values, they were combined in a radar chart graph (or spider diagram). Then, the comparative index is a function of the polygon area generated in the graph formed by the different categories of indicators that compose it.

This method allowed us to overcome difficulties in analyzing different indicators—calculated by the ratio between environmental and economic variables (e.g., produced tones and financial results)—that when presented in isolation are not sufficient to make a rapid and intuitive comparison about the environmental performance between sectors. The radar chart consists of a polygon whose vertices are the different categories of indicators that compose it. The radar chart has equidistant axes in the same center, so that they all have the same angle. The adjacent axes of the graph along with the line formed by the distance of two points form triangles of at least one known angle. The advantages of using the radar chart as a performance comparison tool are visual explanations about the level of performance achieved, supporting a quick comparison of attributes [35,36].

The radar chart is already being used to compare the relative performance of companies considering a set of sustainability indicators [37]. The use of a radar chart (or spider diagram) allows us to compare the Portuguese and Spanish pulp and paper industries because the polygon area gives a proxy of the level of implementation of the circular economy within the industry in each country. Finally, a comparative index is computed, consisting of the ratio of the areas of the graphs, which represent the set of industries to be compared.

For the generation of the comparative index (IC), the procedure used is the calculation of the area of the polygon [38]. For this, it is necessary to calculate the area of all triangles formed in the radar chart and proceed with their sum. After calculating the area of each triangle, and after adding the areas of all triangles that form the polygon, it is possible to calculate the composite index of the circular economy implementation. This index is intended to compare, quantitatively, the performance of two groups within the same category of indicators. In this case, the larger the area of the polygon in comparison to another, the less the implementation of the circular economy of one sector in relation to another. This quantification, as presented in Equation (3), is given as a percentage.

$$IC = \left(1 - \frac{A_T}{A_T{}^1}\right) \times 100 \tag{3}$$

A_T—represents the total area that is occupied by the polygon;
$A_T{}^1$—represents the total area that is occupied by the largest polygon (worst result).

The comparative index values are on a scale of 0% to 100%, where 0% means that the two groups have the same overall performance (that is, both groups have the same polygon area), 50% means that the best performer group presents two-times better circular economy implementation than the one registered in the worst group, and 100% means that one of the groups presents the maximum performance possible for all the indicators (this is, a value of 0 for the polygon area).

3.3. Data Collection

The inputs ("resource utilization") and outputs ("pollution impact") typical of the pulp and paper industry which will be used to calculate the indicators are described in Table 1. Since these two categories intend to measure the resource efficiency and control the emissions of undesirable substances, the lower this indicator, the better the performance of the same. Table 2 lists the indicators that will be calculated, according to the resources that are typically reused in the paper industry: Water reuse and the use of biofuels. The industrial symbiosis indicator is calculated according to Equation (2), previously presented in Section 2.2.2, considering the total of the produced waste and the sum of by-products used for energy valorization in other industries.

Table 1. Proposed eco-efficiency indicators of inputs and outputs [32,39].

Category	Environmental Variable	Economic Variable	Indicator	Units
Resource utilization	Wood consumption	Pulp production	Wood consumption per ton of produced pulp	m^3/Ton
	Energy consumption	Pulp and paper production	Energy consumption per ton of produced pulp and paper	GJ/Ton
	CO_2 Emission	Pulp and paper production	CO_2 emissions per ton of produced pulp and paper	Ton/Ton
Pollution control	Inefficiency of water usage	Pulp and paper production	Residual water rejection per ton of produced pulp and paper	m^3/Ton
	Waste disposal in landfill	Pulp and paper production	Waste disposal in landfill per ton of produced pulp and paper	kg/Ton

Table 2. Proposed reuse indicators [32,39].

Category	Environmental Variable	Indicator	Units
Resource utilization/Reuse	Water	Water reuse rate	%
	Wood/Energy	Use of biofuels rate	%

The specific secondary data that were used to calculate the indicators are presented in Table 3.

Table 3. Secondary specific data used to calculate the sustainability indicators.

Indicator	Specific Data
Wood consumption	- Total of wood consumption - Pulp production
Energy consumption	- Total of electric power consumption - Total production of pulp and paper
Inefficiency of water usage	- Liquid effluents rejection - Total production of pulp and paper
CO_2 Emissions	- CO_2 Emissions - Total production of pulp and paper
Solid waste deposition in landfill	- Solid waste deposition in landfill - Total production of pulp and paper
Water reuse	- Total water captation - Total production of pulp and paper
Industrial symbiosis	- Solid waste destination - Total waste production

4. Results

4.1. Results of Eco-Efficiency Indicators

In the pulp and paper industry, the eco-efficiency assessment involves the quantification of the following categories of indicators: Wood utilization, energy consumption, inefficiency of water usage, CO_2 emissions, and solid waste depositions in landfill. Since these indicators show the resources' efficiencies and control undesirable substances' emissions, the lower the indicator, the better the performance of the indicator.

4.1.1. Wood Consumption Indicator

The wood consumption indicator indicates the consumed wood per ton of produced pulp. The results for this indicator for the two groups of pulp and paper companies are shown in Figure 1. From Figure 1, through the calculation of the averages of the five years, it can be concluded that the specific consumption of wood is 2% higher in Portugal than in the same sector in Spain. From this value, it is concluded that there are no significant differences in the specific use of wood between the two countries.

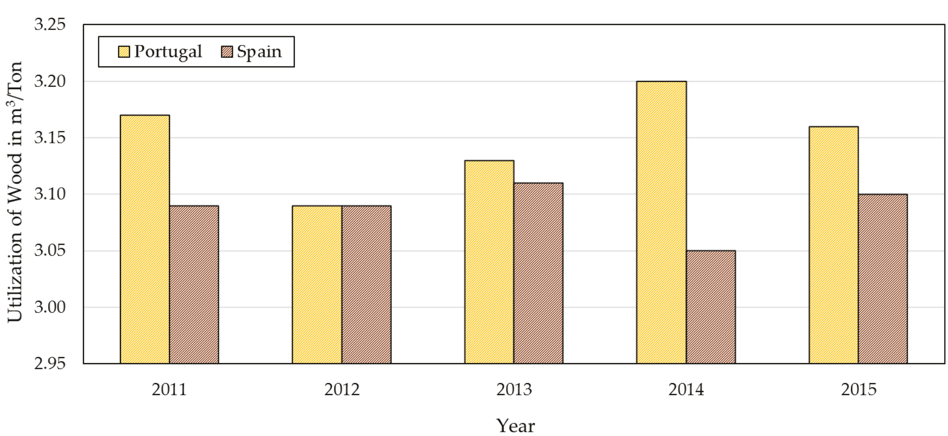

Figure 1. Wood consumption indicators for the pulp and paper sectors in Portugal and Spain.

Although we do not know the details of the different technologies used in the two groups of pulp and paper companies, there are conditions/procedures during the pulp manufacturing process that may affect the efficiency of the wood utilization. These procedures include the density of wood, species of wood used, moisture present in the wood, process losses, wood shattering, and/or wood yield in the baking and bleaching process. Through the period that was studied, the variations in the wood utilization for the two groups of pulp and paper companies may have been due to the need to use imported wood (outside the Iberian Peninsula).

4.1.2. Energy Consumption Indicator

The energy consumption indicator gives information about the electric energy consumed per ton of pulp and paper. The values of this indicator for the two groups of pulp and paper companies are shown in Figure 2.

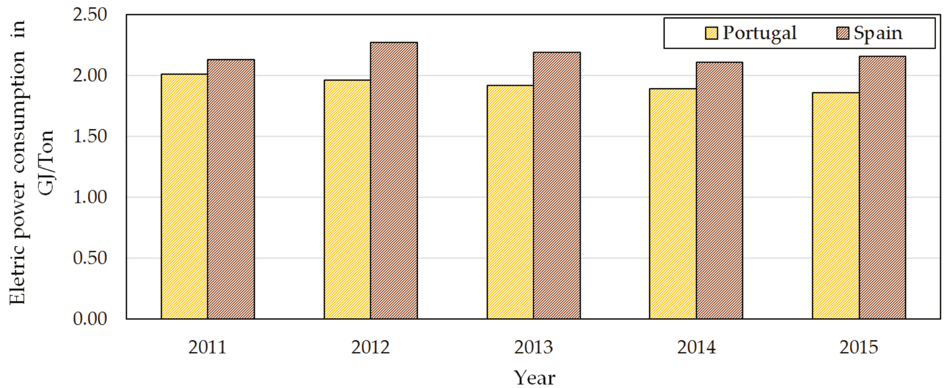

Figure 2. Energy consumption indicators for the pulp and paper sectors in Portugal and Spain.

From the values shown in Figure 2, it is possible to verify that there is a downward tendency of about 7.5% in the specific consumption of energy in the sector in Portugal, and constant consumption of energy in the sector in Spain. After calculating the average of the years under study, it is also possible to verify that the indicator of energy consumption of the sector in Spain is higher than the one registered in Portugal by about 11.3%.

Although there are no details about the techniques used in the two groups of pulp and paper companies, there are procedures during the pulp and paper manufacturing process that may affect its energy efficiency. For example [12]: Energy efficiency levels of the pulp and paper production equipment/machines, paper and cardboard manufacturing process, level of use of systems driven by electric motors, efficiency in the production of heat and cooling, and/or level of efficiency in the industrial process.

4.1.3. Inefficiency of Water Usage Indicator

The inefficiency of water usage indicator reports the amount of liquid effluents that are discarded per ton of pulp and paper. To calculate this indicator, the ratio between liquid effluent rejection and total production of pulp and paper is calculated.

Since this study aims to make a comparison between countries in the same sector, a calculation method based on the following assumptions was used to calculate the indicator for the liquid effluent rejection in the pulp and paper sector in Spain:

- Due to its nature, pulp production uses more fresh water on a specific consumption basis than paper production. This leads to a greater liquid effluents flow than paper production;

- The sector in Portugal produces more pulp in relation to the total production than the sector in Spain;
- The comparison should be fair, so based on the two previous assumptions, data indicating the consumption of pulp and paper should be used in a discriminatory manner, if they are available;
- It was not possible to find separate data for specific effluent flows from the pulp and paper sector in Portugal;
- The sector in Spain has discriminated data for the pulp and paper production.

Following this logic, the liquid effluent rejection indicator for the period under study was calculated as follows in Equation (4):

- The specific rejections of liquid effluents from the sector's pulp and paper productions in Spain were multiplied by the respective pulp and paper productions in Portugal. In this way, it is possible to calculate the aggregate rejection of liquid effluents (considering that the sector in Spain had the same production levels as in Portugal).
- The result was divided by the total production of the sector in Portugal.

$$IELSE = \frac{RE_{Pulp}SE \times P_{Pulp}SP + RE_{Pap}SE \times P_{Paper}SP}{P_{Total}SP} \quad (4)$$

IELSE—Liquid effluent rejection indicator of the sector in Spain;

$RE_{Pulp}SE$—Liquid effluent rejection in the sector in Spain, related to the pulp production per ton of produced pulp (m^3/Ton);

$P_{Pulp}SP$—Pulp production in the sector in Portugal;

$RE_{Paper}SE$—Liquid effluent rejection in the sector in Spain, related to the paper production per ton of produced pulp (m^3/Ton);

$P_{Paper}SP$—Paper production in the sector in Portugal;

$P_{Total}SP$—Total production in the pulp and paper sector in Portugal.

In this way, it is possible to compare the pulp and paper sectors in the two groups of pulp and paper companies at an aggregate level in a more equitable way. The results of the indicator in Portugal and Spain for the different years are presented in Figure 3.

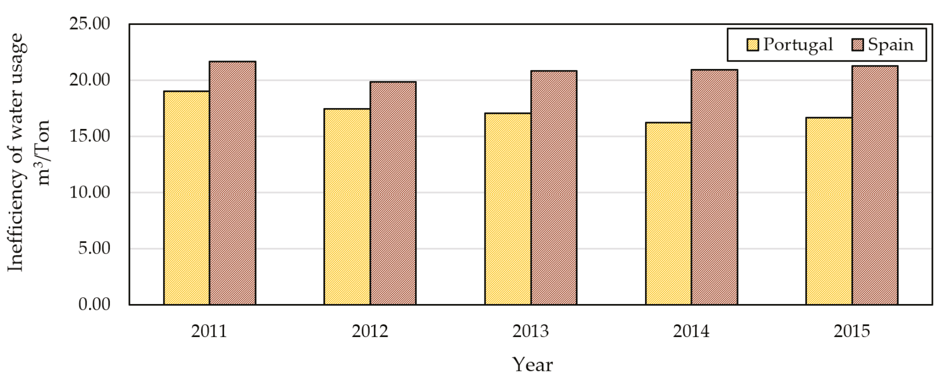

Figure 3. Inefficiency of water usage for the pulp and paper sectors in Portugal and Spain.

Based on the calculations, from the data shown in Figure 3, it can be concluded that with the specific individual consumption data per specific type of product, in the sector in Spain, if this same sector produced the same amounts of those different products, it would be about 17% less efficient in the water usage in their process than the sector in Portugal.

Although there is no information about the techniques used in both countries, these discrepancies may be due to [12]: Efficiency in industrial operations, efficiency of pulp washing, type of pulp bleaching, type of wood cooking, separation level of water circuits, pulp washing techniques, and/or level of monitoring of water spills.

4.1.4. CO_2 Emissions Indicator

The CO_2 Emission indicator assesses the emission of CO_2 gases that are emitted per ton of produced pulp and paper. The calculation of this indicator is made through the ratio between CO_2 emissions and total production of pulp and paper. The results for both countries are shown in Figure 4.

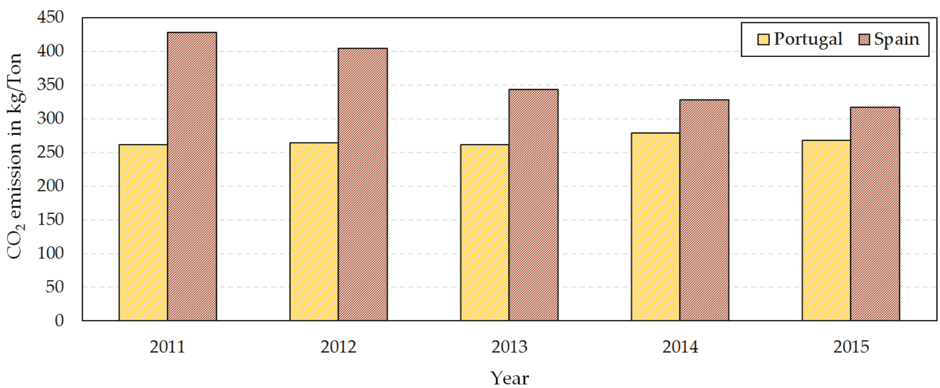

Figure 4. CO_2 emissions indicators for the pulp and paper sectors in Portugal and Spain.

After calculations from the data presented in Figure 4, it is possible to conclude that there was a constant performance in Portugal, and a decrease of 36% in CO_2 emissions in Spain, in the period of study. However, on average, the specific emissions of CO_2 in the sector in Spain are 16.8% higher than those registered in the sector in Portugal. Since most of the emissions are due to the burning of fossil fuels for energy production, these results could come from the Spanish sector's strategy for its energy self-sufficiency.

Although there is no information about the techniques used in both countries, the causes of the differences in values may be in [12]: Practices for the use of clean energy, level of control of the emissions from biomass combustion and fossil fuels, optimization of combustion, level of gas incineration practices, and/or level of gas washing practices.

4.1.5. Solid Waste Deposition on Landfill Indicator

The solid waste disposal on landfill indicator gives information about wastes that are produced and deposited in landfills per ton of produced pulp and paper. The calculation of this indicator is made through the ratio between the total deposition of waste in landfill and the total production of pulp and paper. The results are shown in Figure 5.

From the values presented in Figure 5, it is possible to calculate a decrease of of approximately 45.8% and 29.4% in the deposition of solid residues in landfill for the Portuguese and Spanish pulp and paper companies, respectively. However, on average for the five years, it is estimated that the sector in Portugal had a solid waste deposition in landfill of about 49.5% lower than the one registered in the sector in Spain.

Although there is no information about the techniques used in the two groups of pulp and paper companies, the differences in results in both countries may have the following causes [12]: Level of implementation of industrial symbiosis, solid waste destination, level of waste assessment, waste assessment systems, and/or type of waste pretreatment prior to the reuse.

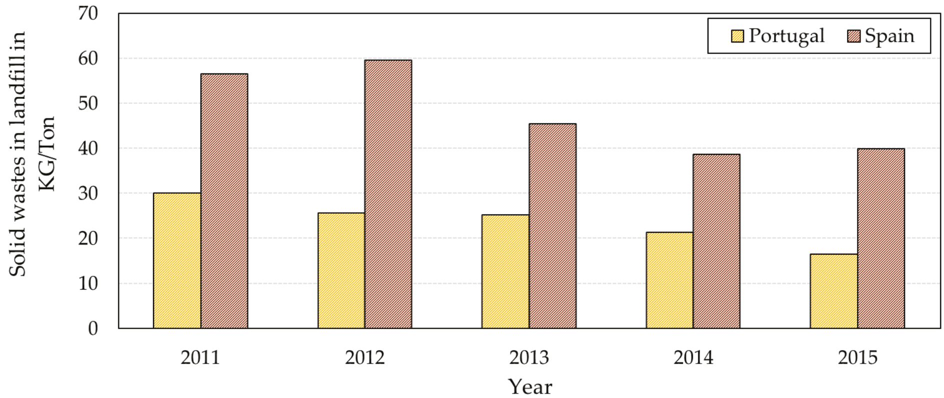

Figure 5. Solid wastes disposal indicators for the pulp and paper sectors in Portugal and Spain.

4.2. Results of Reuse and Industrial Symbiosis Indicators

Since reuse and industrial symbiosis indicators quantify the reuse of resources and not their use, these indicators have a different function from the production-based indicators. Reuse and industrial symbiosis indicators also differ in the evaluation of results, since for these, the greater the percentage obtained by the ratio between a reused resource and the total resource used, the better the environmental performance of the resource. To evaluate reuse in the pulp and paper sector, the following indicators were used: Reuse of water, use of biofuels, and industrial symbiosis.

4.2.1. Water Reuse Indicator

To calculate the water reuse indicator, the ratio between the water that is rejected in the pulp, paper, and cardboard (or liquid effluent) production processes and the total volume of water that is collected is calculated. The results of the indicator are shown in Figure 6.

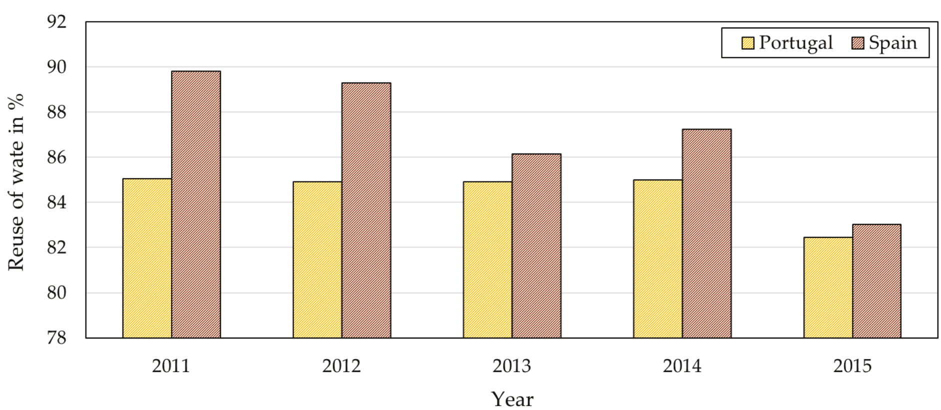

Figure 6. Water reuse indicators for the pulp and paper sectors in Portugal and Spain.

From Figure 6, it is possible to conclude that there is a constant trend in the water reuse numbers in both the Portuguese and Spanish sectors. There is one exception in the year 2015, where it is possible to observe a marked decrease in both countries. It is also possible to conclude, after the respective calculations, that the sector in Spain reuses an average of 2.66 percentage points more water than that which is reused in the sector in Portugal.

Although there is no information about the techniques used in the two groups of pulp and paper companies, differences in the results could have the following causes [12]: Monitoring of water waste, level of water recirculation, water use efficiency level, liquid effluent treatment level, and reusable water levels in the industry.

4.2.2. Use of Biofuels Indicator

The paper industry uses biofuels, such as residual biomass from forest exploitation and black liquor, in great amounts for energy production. For the sector in Portugal, these indicators were provided directly by CELPA. In the case of Spain, these data were taken directly from the statistical bulletin ASPAPEL. The results from this indicator are presented in Figure 7.

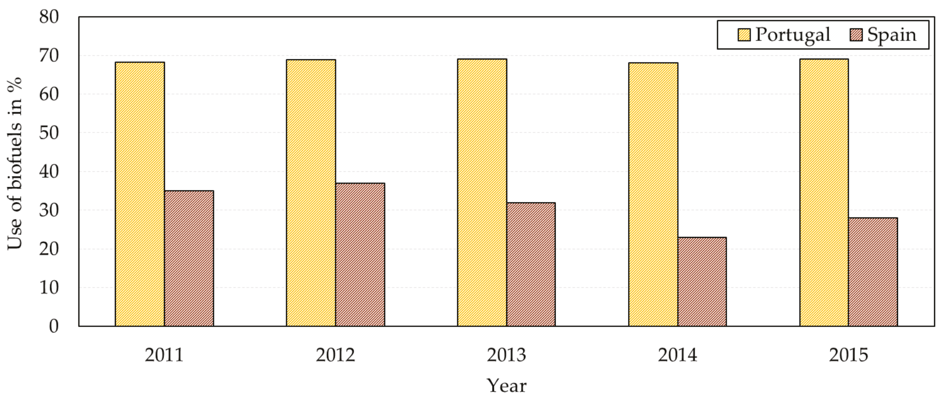

Figure 7. Use of biofuels indicators for the pulp and paper sectors in Portugal and Spain.

As Figure 7 shows, the biofuel utilization value of the sector in Portugal is considerably higher than in Spain, and there is a difference that exceeds 40 percentage points in some years. It is also possible to verify that the use of biofuels is constant in the sector in Portugal, and the existence of a tendency to decrease in the use of biofuels in the sector in Spain.

These results may be due to the strategy used in the sector in Spain, such as less biomass-based energy and production, more cogeneration plants supplied with natural gas, or more fuel-based boilers. The latter can be motivated by economic causes or by the lack of infrastructure that allows for greater use of biomass for energy production.

4.2.3. Industrial Symbiosis Indicator

Data regarding waste which is used in industrial symbiosis is calculated by the sum of the waste and by-products used for energy valorization for other industries, like the ones that are used in the ceramic and cement industry, as well as those used as secondary raw materials for other industries. The calculation of this indicator is made according to Equation (2).

The values for this indicator are shown for both countries in Figure 8. From this figure, it can be concluded that for the sector in Portugal, the year 2015 was the year in which there was a lower symbiotic relationship, in contrast to the year 2014 that had the best result in the period between 2011 and 2015.

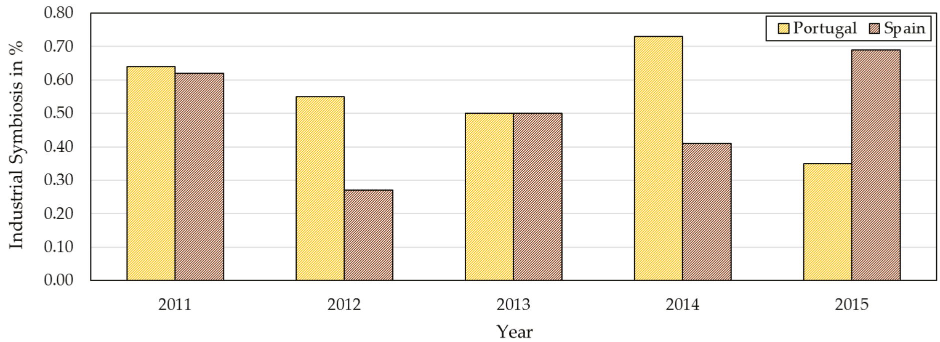

Figure 8. Industrial symbiosis indicators for the pulp and paper sectors in Portugal and Spain.

4.3. Results from the Comparative Analysis of the Circular Economy

Through the elaboration of a radar chart (or spider diagram) for each of the years studied, it was possible to analyze the indicators. After calculating the areas of the indicators, the two sets of companies were compared by calculating the comparative index. These results serve as an analysis of the evolution of the circular economy implementation for the years between 2011 and 2015.

In the five years studied, when comparing to the environmental variables of the sector in Spain, the sector in Portugal stood out in the categories of: Electricity consumption, liquid effluent rejection, CO_2 emissions, the use of biofuels, landfill, and industrial symbiosis. The sector in Spain had a better environmental performance in the categories of indicators related to the use of wood and water reuse.

As previously shown in Section 3.2, it is necessary to convert the indicated values to normalized values. In the case of indicators whose base is production, the normalization method is to make the ratio between each result by the less favorable value of the respective category. In this way, the smaller the area of the radar chart, the better the eco-efficiency of the sector. In order to normalize the values of the reuse and symbiosis indicators, it is necessary to divide the less favorable value by indicators of the respective category. After normalization, the set of categories of indicators presented is collected in a radar chart.

Figure 9 shows the radar chart corresponding to the last year under study, 2015. The value of the comparative index is 26.16%. Since this result represents the proxy for the level of implementation of the circular economy from one country to another, it is possible to conclude that the sector in Portugal has a 26.16% better implementation than the one registered in Spain.

Figure 10 presents the areas of the polygons that represent the implementation of the circular economy in the years under study.

The comparative index, calculated by the ratio between the areas of the polygons of the respective countries, is also represented. Based on Figure 10, it can be concluded that the area of the polygon representative of the implementation of the sector's circular economy in Portugal is smaller than the representative polygon of the sector in Spain during the studied period. Thus, and as can be seen from the comparative index, the pulp and paper sector in Portugal has a higher implementation of the circular economy procedures when compared with Spain.

However, in spite of the successive positive results of the sector in Portugal, in relation to the sector in Spain, in the year of 2015, there was a decrease in the comparative index. Several reasons could be behind this result. However, in part, this could be explained by the implementation of the circular economy in the sector in Spain [38,39].

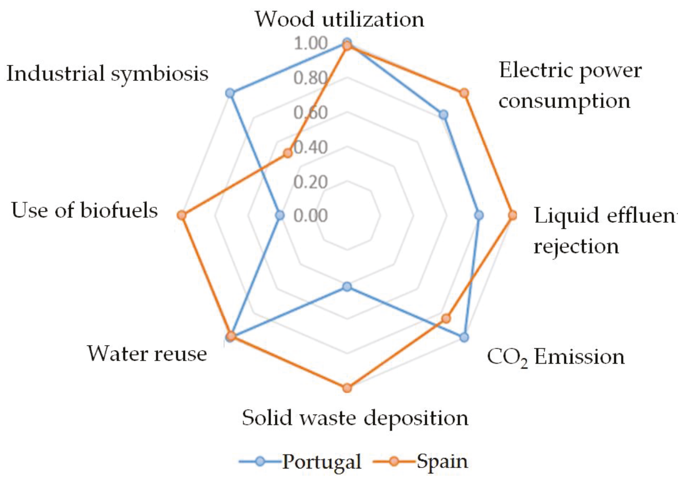

Figure 9. Circular economy representation in the pulp and paper industries in Portugal and Spain in 2015.

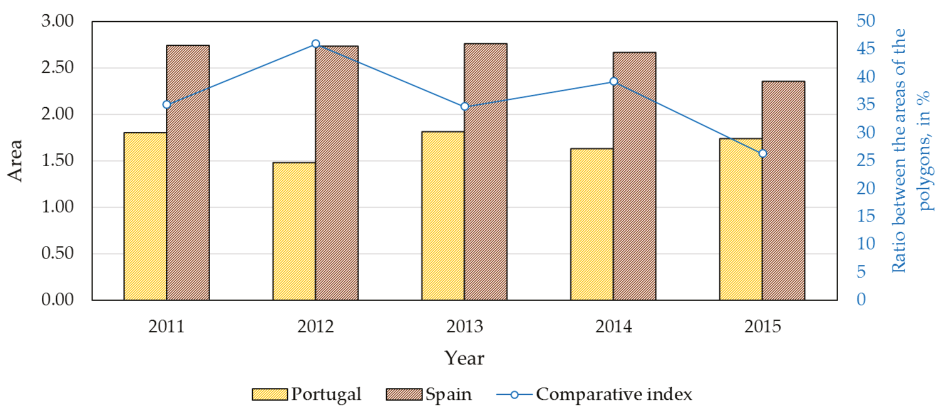

Figure 10. Comparative indexes for the sectors in Portugal and Spain in the years under study (2011–2015).

5. Conclusions

This research allowed us to identify, calculate, and analyze the evolution of the circular economy and eco-efficiency implementation in the pulp and paper sectors in the Iberian Peninsula between 2011 and 2015. This analysis was possible through the calculation of specific indicators of the sector under study, such as: Wood consumption, electric energy consumption, CO_2 emissions, inefficiency of water usage, waste disposal in landfill, biofuel use, water reuse, and industrial symbiosis. From these, it was found that the sector in Portugal consumed 11.3% less electricity, on average, in the period under study; was 17.3% more efficient in water usage; emitted 16.8% less CO_2; used 37.7 percentage points more of biofuels; sent 49.5% less waste to landfill; and has a 19.13% higher implementation of industrial symbiosis than the sector in Spain. It was also possible to conclude that the sector in Spain uses 2% less wood than the sector in Portugal, and reuses 2.7 percentage points more water than the sector in Portugal.

Radar charts representing the circular economy in the pulp and paper sectors were created for Portugal and Spain. From these results, it was possible to conclude that, through the calculation of the comparative index, the sector in Portugal had an implementation of the circular economy 34.98%, 45.89%, 34.65%, 39.13%, and 26.21% higher than the sector in Spain in the years between 2011 and 2015, respectively.

It is very important to emphasize that the most important and valuable contribution of this paper is to explain and deliver a methodology to evaluate and eventually compare the eco-efficiency performances and the degrees of circular economy implementation of an industry. The practical example used (the analysis and comparison of a group of industrial Iberian companies belonging to the pulp and paper industry) needs to be seen as an exercise to demonstrate the utilization of the method. The sectors in both countries are very different, with Portugal showing a very strong and huge capacity for pulp production as well as uncoated fine paper production (Office and Offset Paper), while in Spain, the packaging paper based on secondary (recycled) fiber is of paramount importance. These substantial differences might justify some of the obtained figures.

As a suggestion for future research, it is recommended to apply the comparative index developed in the present research by extending the study to the European pulp and paper industries, particularly in the Nordic countries. In these countries, the circular economy is in great development and under constant improvement. The comparison with these countries would be beneficial in understanding the position of Portugal in relation to an industry that is leading the way in the application of the circular economy. Another potential study could be addressing the socio-economic dimensions of the circularity of this sector, and making an association between the economic and social attributes with the proposed environmental sustainability indicators.

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Development of an Optimization Method and Software for Optimizing Global Supply Chains for Increased Efficiency, Competitiveness, and Sustainability

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Abstract: Presently, an increasing human population, customer consumption, and global market competition result in the reduction of natural resources and growing environmental damage. Therefore, the current practice in the use of resources is not sustainable. The production companies have to focus not only on cost-effective and profitable operation, but at the same time environmentally friendly and sustainable production in order to increase competitiveness. New innovative technologies are required, improving the efficiency of the processes and the optimization of global supply chains (GSC) in order to establish sustainability in environmental, social, and economic aspects. The aim of the study is the GSCs' optimization, which means forming the optimal combination of the chain members (suppliers, final assemblers, service providers) to achieve cost-effective, time-effective, and sustainable operation. This study introduces an elaborated single- and multi-objective optimization method, including the objective functions (cost, lead time) and design constraints (production and service capacities; volume of inventories; flexibility and sustainability of the chain members). Based on the elaborated method, software has been developed for the optimization of sustainable GSCs. The significance and novelty of the developed method and software is that the chain members have been required to fulfill the sustainability design constraint built into the software. A real case study is introduced, for the optimal design of a sustainable GSC, to confirm that our developed optimization method and software can be applied effectively in practice for the optimization of both profitable and sustainable GSCs.

Keywords: sustainable global supply chain; single- and multi-objective optimization method; sustainability design constraint; software application; real case study

1. Introduction

The changing global market environment, increasing human population, rapidly changing customer demands, and growing environmental damage have resulted in significant changes in the production sector. Production philosophies have changed from the traditional mass production to the Industry 4.0 concept. The supply chains have been globalized, cooperation between chain members has become more dynamic, and more complex networks of GSCs have been formed.

The supply chain is a system of supply chain members, which are production companies (suppliers, final assembler), service providers and customers as well as their production and service activities. The supply chain is the process of manufacturing finished products from natural resources, raw materials, and components and the delivery of the finished products to the end customers [1]. Continuous material and information flows and value-adding activities among the supply chain members maximize profitability and satisfy customers [2,3].

In production, the resources (raw materials, humans, machines, energy, etc.) are limited and the human population is increasing, so the current practices in the use of resources are not sustainable [1,4]. Therefore, the enterprises have to focus on cost reduction, productivity, and profitability, but at the same time have to establish environmentally friendly and sustainable production in order to increase competitiveness. New production philosophies, advanced materials, higher amounts of renewable resource usage, innovative and environmentally friendly technologies, and processes with improved efficiency and optimized GSCs are required in order to establish sustainability [1,4].

Sustainability is defined as the satisfaction of the present needs of the human population without compromising future generations' ability to meet their own needs [5,6]. In earlier articles sustainability focused on environmental issues, but later on the 'triple bottom line' approach to sustainability was increasingly applied [2]. Most of the relevant literature discusses the concept of sustainability based on three main aspects as follows: Environmental, social, and economic ones. Environmental sustainability means efficiency in resource utilization, recycling and reduction of pollution, waste, and emissions [7]. The social aspect means the compliance with human rights and labor laws, the adoption of social standards (ISO 26000), and impact on local communities [8,9]. Social sustainability includes critical areas which provide health and safety, working conditions, human rights, and community programs [10,11]. The economic aspect means the achievement of the targeted long-term economic performance according to operational metrics [4,7].

Recently, several publications have criticized the above-mentioned limited interpretation of the triple bottom line. In the literature the number of publications in which the definition of sustainability is discussed in a more holistic view is increasing. For instance, in their article Ahy and Searcy concluded that the main characteristics of sustainability are economic focus, environmental focus, social focus, stakeholder focus, volunteer focus, resilience focus, and long-term focus [2].

The optimization of sustainable GSCs is part of the GSC management's activity and is an important and essential tool for the optimal formation and operation of efficient, profitable, and sustainable GSC networks. Sustainable supply chain management means the management of material, information, and capital flows, as well as cooperation among companies along the supply chain, while taking into account goals from all three dimensions of sustainable development—economic, environmental, and social; derived from customer and stakeholder requirements [2,12,13]. The sustainable supply chain not only makes a profit, but also bears responsibility to its consumers, suppliers, societies, and environments in the innovative strategic, tactical, and management technologies employed [12,14].

The primary aim of the study is to develop an optimization method and software which provides the creation of an optimal combination for sustainable GSCs' members (suppliers, service providers, final assemblers) to achieve not only cost-effective and time-effective but, at the same time, sustainable operation. Our developed method and software are an additional contribution to the recent state of the research field because, by the application of the software, only sustainable optimal GSCs can be created since sustainability as a design constraint is built into the method and software. Another aim of the study was to test whether our developed optimization method and software can be applied effectively in a company-based case study on the optimization of sustainable GSCs.

The significance of the topic is that the optimal formation and operation of the sustainable GSCs provide the efficiency, profitability, and sustainability of the whole GSC networks. The optimal formation of the sustainable GSC, which provides competitiveness for all members of the GSC, is an important strategical decision of the GSC management. These management decisions are supported by our method and software.

The structure of the study, main essences, and added values of the sections are the following:

1. In the literature review section, the relevant articles concerning the research topic are introduced. Based on the synthesis of the recent literature it can be concluded that, although the design of supply chains is often discussed, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods, which can be found in existing literature, use a limited number of design constraints. The sustainability design constraint is not taken into

consideration during the optimization, while the flexibility design constraint is available only in some publications, but in these articles the meaning of the flexibility is not detailed enough. Therefore, our developed method and software are an additional contribution to the recent state of the research field because it is the first time the literature takes sustainability and flexibility constraints into consideration simultaneously.

2. In Section 3 the our elaborated single- and multi-objective optimization method is introduced, as well as the objective functions, (1.) cost and (2.) lead time, and design constraints, (1.) capacity constraints for production and service activities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain's members and (4.) constraints for the sustainability of the chain's members. Software has been developed based on the elaborated optimization method, which can be applied for the optimization of profitability and at the same time as sustainable GSCs.

Our developed method and software are novel and provide an additional contribution to the recent state of the research field because, in addition to the generally applied design constraints, both sustainability and flexibility design constraints are also built into the method and software.

Sustainability design constraint means that the potential suppliers and service providers can only be members of a sustainable GSC if these companies fulfill the sustainability requirements. Since all of the members of the GSC have to fulfill the sustainability constraints, an optimal GSC can be formed by applying the software, which is not only cost- and time-effective (as in cases of the other optimizing software) but at the same time sustainable. In the literature, it is the first time that potential supply chain members' ability to fulfill the sustainability requirements has been analyzed.

Flexibility constraint means the capability of the chain members for adapting to changing market demands. The flexibility and financial liquidity of the GSCs' members are analyzed and evaluated. The flexibility includes the following: Resource flexibility; flexibility of the organization structure; strategic flexibility; and flexibility for collaboration between production companies, service providers, and stakeholders [15].

The systematic search method was used for single-objective optimization, while the multi-objective optimization was performed by the systematic search method combined with the normalized weighting method. In case of the multi-objective optimization, due to the weighting method, depending on the design strategy (type of final product; customers' requirements; location of the customers; living standard of the customers; type of industrial sector; competitors' products; etc.) the GSC management has to define whether the cost or the lead time is the more preferred design aim. Therefore, the ratio of the objective functions must be set arbitrarily in the software (e.g., 75% cost—25% lead time). In case of different ratios of the objective functions, different optimal combinations of GSCs can be formed from the same potential suppliers and service providers.

It can be concluded that the sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions, because the sustainability constraints are built into the software.

If the more important strategical aim of the management is the minimization of the total cost of the GSC, the ratio of the cost objective function has to be higher than the lead time objective function. It is often used if the most important aspect for the customers is the low cost of the products (e.g., traditional basic commodities; the customers are cost sensitive due to their living standard or their location). On the contrary if the customers are not cost sensitive (e.g., fashion industry, high-tech products, luxury products with portfolios that change very fast) but the most important requirement is the shortest delivery time, then the ratio of the lead time objective function has to be higher [1,15].

In Sections 4.3.1–4.3.4 a real case study is introduced to confirm that our developed method and software can be applied effectively, in practice, for the optimization of sustainable GSCs. A case study is introduced for the optimal design of a sustainable GSC by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from more potential suppliers and service providers for three cases as follows: (1.) Total cost minimization of the GSC, (2.) total lead time minimization of the GSC, and (3.) in case of different ratio of the objective functions (60% cost–40% lead time).

It can be concluded that our developed method and software is an additional contribution to the recent state of the research field because, by the application of the software, only sustainable optimal GSCs can be created, in case of every kind of ratio of the objective functions, since sustainability as a design constraint is built into the method and software.

2. Literature Review

A great deal of literature was evaluated relating to the research topic, which provided the theoretical background of this study. The most important logistical and production goal is maximal customer satisfaction; all of the other goals can be derived from this. Customer demands define the applied production philosophies [16]. The production philosophies have been changed from the traditional mass production to the Industry 4.0 conception. The main aim of the Industry 4.0 paradigm is the establishment of network-linked intelligent systems, which perform self-regulating production in which people, machines, equipment, and products communicate with one another. Industry 4.0 will bring the age of collaborating and intelligent industrial robots [1]. The production conceptions determine the characteristic of the supply chains [16].

2.1. Global Supply Chain Networks

The supply chain is a system of supply chain members (suppliers, final assemblers, service providers, and customers) and their production and service activities. The supply chain is the process of manufacturing finished products from natural resources, raw materials, and components and the delivery of the finished products to the end customers [1]. Global supply chains are supply chains that extend beyond a single country's boundaries [12].

- The members of GSCs (Figure 1): Manufacturing companies [final assemblers (FA); suppliers (S_j)]; service providers (SP_m) [logistics, IT, financial, etc. service providers] (detailed in Figure 2); and customers (C_l) [consumers, wholesalers, retailers, end-customer, etc.].
- The types of the service providers are the following (Figure 2): Logistics service providers (transporting, forwarding, warehousing, SC managing, etc. companies); information service providers (IT enterprises, telecommunication companies, etc.); research & development service providers (research institutes, consulting enterprises, universities, etc.); and financial service providers (lease brokers, banks, etc.).

In the last decades of the 20th century the fast-changing market environment and global competition resulted in more complex networks of supply chains. Value chains were globalized and GSC networks were formed. The cooperation between the enterprises became more dynamic. GSCs are thus characterized by focal firms that distribute across multiple countries, locate production facilities abroad, or source from offshore suppliers [17]. The focal firms seek to secure a competitive advantage by employing competent and low cost suppliers, located around the world [18]. The distance separating a focal firm and its suppliers is thus greater, as is the number of suppliers in the GSC [12].

The key of success for GSCs is to understand and fulfill customer demands. The competitiveness of the chain members originates from the utilization of the advantageous characteristics of the members. In the global market the GSCs compete together to fulfill the customer demands maximally, with high quality products or services. Customers choose between the GSCs by buying the best finished product or service. The main aspects of the customers' decision making are the cost of the final product, total lead time, product quality, product customizability, and the quality of additional services connected to the final product.

A great deal of literature reviews the definitions, properties, and types of GSCs [19–22]. More complex GSCs have been formed and novel GSC concepts (1. Lean; 2. Agile; and 3. Hybrid) have been established alongside the traditional chains due to fluctuating and unique customers' needs in order to maintain and increase the competitiveness of the GSCs' members [23].

The main goal of the Lean Supply Chain concept is to minimize waste by eliminating non-value adding activities and improving the processes continuously. The members of the lean supply chains apply the lean manufacturing philosophy, which is the most widely used conception and efficiency improvement method in many production and service sectors [24,25]. The main characteristic of Agile Supply Chains is their agility, referring to the connection between the company producing the finished product and the customer market. It means flexible adaptation to fast-changing customer demands [23,26,27]. The Hybrid Supply Chain is a combination of lean and agile supply paradigms, which utilizes the advantages of both conceptions.

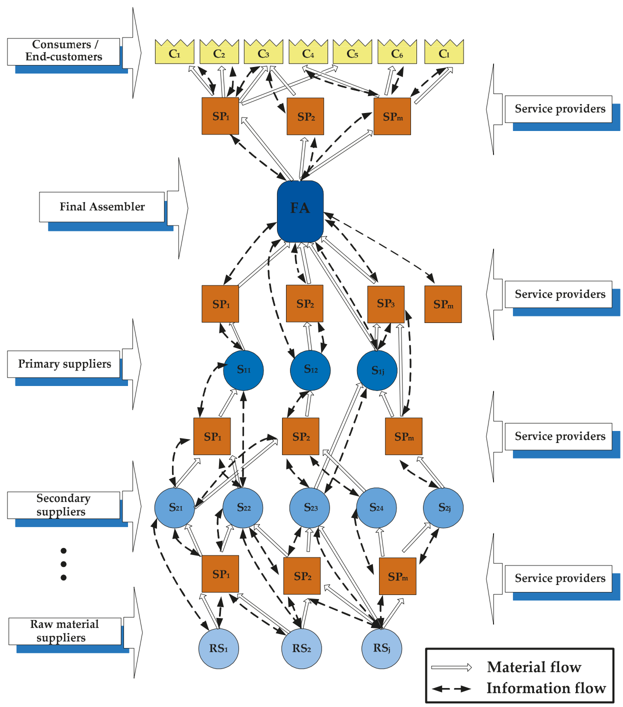

Figure 1. Network of a Global Supply Chain. Source: Own.

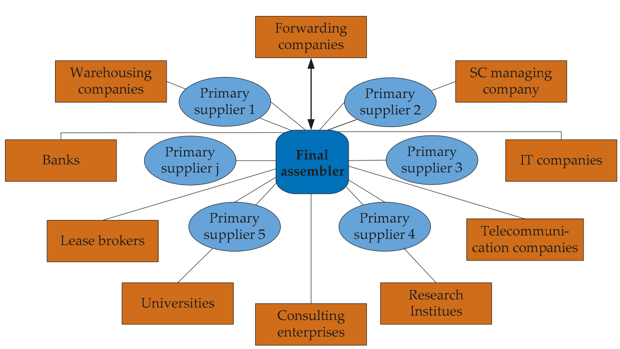

Figure 2. Types of service providers in the GSCs. Source: Own.

2.2. Sustainable Global Supply Chains

Environmental damage has become a global problem and sustainability has become increasingly important. In the production sector, resources are limited and the human population is continuously increasing; therefore, recent practices in the use of resources are not sustainable.

In earlier articles the sustainability only focused on environmental issues, but later on increasingly applied the environmental, social, and economic approach to sustainability [2]. The economic aspect means production by cost, energy, and material efficiency and innovative production technology to achieve profit. The environmental aspect means production using renewable resources and raw materials that are safe for the environment, workers, and customers. The social aspect means compliance with human rights, labor laws, and safety-at-work rules. If the GSC is completely sustainable, it will not cause damage to ecosystems or social systems and, at the same time, it will bring profits in the long term [28,29]. Presently, several articles have criticized the above-mentioned limited interpretation of the Triple Bottom Line (TBL). Elkington coined the phrase 'TBL' in 1994, then, in his article published in 2018, he also suggested that 'it's time to rethink it' in a wider sense [30]. In the literature the number of publications in which the definition of sustainability is discussed in a more holistic view is increasing. Some studies have included further requirements for sustainability, e.g., stakeholder focus, volunteer focus, resilience focus, and long-term focus, etc. [2].

Consequently, the enterprises of the GSCs have to focus on cost reduction and profitability while also establishing environmentally friendly and sustainable production and services. Therefore, innovative and environmentally friendly technologies are needed, together with the efficiency improvement of the processes and the optimization of GSCs is required in order to establish sustainability.

Definitions and characteristics of supply chain management appear frequently in the literature. Simchi-Levi et al. defined the supply chain management as a set of approaches to integrate elements of a supply chain to minimize total system cost while maintaining adequate production and service levels [31]. There are strategic, tactical, and operational dimensions in supply chain management [32].

Sustainable supply chain management means the management of material, information, and capital flows as well as cooperation among companies along the supply chain, while taking into account goals from all three dimensions of sustainable development (economic, environmental, and social), derived from customer and stakeholder requirements [12,13].

Production companies have to establish sustainable production, while service providers have to provide sustainable services. The following two activities of sustainable GSCs are particularly damaging to the environment: (1.) Production activity of manufacturing companies (final assemblers and suppliers) of GSCs and (2.) transportation (activities of transport service providers).

2.2.1. Sustainable Production in the Global Supply Chain

The essence of sustainable manufacturing is that the hazardous impacts of manufacturing operations on the environment have to be minimized while optimizing the production efficiency of the company [33]. Sustainability orientation concerns the redesign of enterprises' products and manufacturing processes, taking environmental and social regulations into consideration [34–36].

The Lowell Center for Sustainable Production (LCSP) defines sustainable production as the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people [37,38]. The LCSP and other authors also describes the following main elements of sustainable production as well: Energy and material use, the natural environment, social justice and community development, economic performance, workers, and products [34,37,39].

Principles of Sustainable Production

Based on the above-mentioned publications [37–39] the following nine principles of sustainable production can be summarized. The manufacturing practices relating to the nine principles of sustainable production [40] is detailed in Appendix A.

1. Sustainable design of products: Products are designed to be cost-efficient, competitive, safe, durable, and produced by energy-efficient, material-efficient, and innovative production technology (economical asp.). Furthermore, the products should be environmentally and user-friendly, easily recyclable, renewable resources will be used during the production, and the use of raw materials and final products will be safe for the environment, the workers, and the customers (environmental asp.).
2. Energy and materials efficiency during the manufacturing of products: Efficient usage of the energy and materials during the manufacturing of products from raw materials and components.
3. Elimination or recycling of wastes: Wastes and unusable by-products have to be minimized, eliminated, or recycled.
4. Substitution or elimination of hazardous materials and technologies in manufacturing processes: Chemical substances or physical agents and conditions that present hazards to human health or the environment have to be eliminated, focusing on hazardous emissions into air and water and on hazardous physical agents, technologies, or work practices.
5. Establish safe workplaces and technologies: Workplaces and technologies are designed to minimize or eliminate chemical, ergonomic, and physical hazards and to reduce the risks workers are exposed to.
6. Management activity for continuous evaluation and improvement of processes on economic, environmental, and safety aspects: Management is committed to an open and participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the company. Practices are aimed at reducing environmental health and safety compliance costs, improving participatory management style, promoting stakeholder involvement in decision making, and increasing customer satisfaction; all of which enable company profitability.
7. Motivation of employees in order to improve the efficiency and creativity: Work is organized to maintain and increase the efficiency and creativity of workers. Practices aim to improve workers' efficiency and creativity, and establish reward systems.
8. Social advantages and advancement possibilities for employees: The safety and wellbeing of all employees is a priority, as is the continuous development of their talents and capacities. It is important to provide opportunities for employee advancement, job satisfaction, training, gender equality, and reduction of turnover rate.
9. Development of community-company partnerships: The communities around workplaces are respected and enhanced economically, socially, culturally, and physically. Employment opportunities are provided for locals, developing community-company partnerships.

2.2.2. Sustainable Transport in the Global Supply Chain

Besides production activity, transportation is the other most environmentally damaging and expensive activity of GSCs. Freight transport is performed by transport service providers in GSCs.

Transportation is sustainable in the narrower sense of its environmental, social, and climate impacts, with more integrated solutions and technological innovations. In the global scope it involves the sustainability analysis of transport vehicles used for road, rail, water, or air transport, the source of energy, and the infrastructure of the transportation [41,42]. Short-term activity often promotes incremental improvements in fuel efficiency and vehicle emissions controls while long-term goals include migrating transportation from fossil-based energy to other alternatives, such as renewable energy and the use of other renewable resources [43].

There are two ways for scientific research to support sustainable and environmentally friendly transport. The first way is developing and producing environmentally friendly technologies and equipment (e.g., high-tech engines). Furthermore, scientific research can also support the cost-effective, profitable, and sustainable operation of transport service providers through efficiency improvement methods and decision-supporting software applications. These efficiency improvement methods result in the reduction of fuel consumption and environmental damage. In addition, the companies that are able to achieve higher profits can afford to invest in environmentally friendly technologies and new vehicles, which also results in the reduction of environmental damage.

Practical Tools for Sustainable Freight Transport

- Application of environmentally friendly and innovative technologies (e.g., high-tech engines);
- usage of alternatives such as renewable energy instead of fossil-based energy;
- modernization of the fleet of vehicles;
- optimized utilization of vehicle fleet capacity and human resources;
- more effective cooperation between transport modes (road, rail, water, and air) to increase the ratio of multimodal transportation (the volume of road freight transport in Europe is approximately 80% of the total freight transport volume, which makes up approximately 80% of the total emissions of the freight transportation sector; therefore, the ratio of road freight transportation has to be reduced);
- optimization of transport routes and transport trips, minimization of empty haulage;
- application of information and communication technologies (ICT);
- usage of optimization and decision-supporting software applications;
- application of waste management and recycling;
- monitoring compliance with safety-at-work rules and environmental regulations [1].

2.2.3. Optimization of Global Supply Chains

The optimization of GSCs is an important tool for optimal formation of efficient, profitable, and sustainable GSC networks. In the literature there are several optimization algorithms for network optimization, which can be classified into categories such as scalar methods, fuzzy methods, interactive methods, metaheuristic methods, decision aided methods, etc. [44].

The literature often discusses the most important objectives for supply chain optimization as objective functions as follows: Cost [27,45], profit [46], total lead time [47], customer service level [48], etc. During optimization, the design constraints also have to be defined. The most common constraints used in the design of SCs are the following: Capacity constraint for production and services, constraint for inventories, constraint for location, financial constraints, etc.

It can be concluded, based on the synthesis of the recent literature, that, although the characteristics and significance of sustainable GSCs and the design of GSCs are often discussed, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods, which can be found in existing literature, use a limited number of design constraints. The sustainability constraint is not taken into consideration during the optimization, while the flexibility constraint is only available in some publications, but in these articles the meaning of the flexibility is not detailed enough. Therefore, our developed method and software are additional contributions to the recent state of the research field because it is the first of the literature that takes sustainability and flexibility constraints into consideration simultaneously. This means that during the optimization the potential GSC members have been analyzed regarding their fulfillment of sustainability and flexibility requirements.

3. Single- and Multi-Objective Optimization Method and Software Application for the Design of Sustainable Global Supply Chain Networks

The single- and multi-objective optimization method was elaborated for the optimal formation of sustainable GSCs. It means that manufacturing and delivering of finished products to customers will be the most cost- and/or time-effective. During the optimization, the total cost and/or the total lead time objective functions and four design constraints, including the sustainability constraint, were defined.

3.1. Objective Functions

During the optimization of sustainable GSCs the most important objectives are the minimization of the total cost or/and the minimization of the total lead time, according to the customer satisfaction. Therefore, during the single-objective optimizations the total cost or the total lead time objective functions, while in case of the multi-objective optimization the total cost and the total lead time objective functions, were taken into consideration.

In our study we focused on the main part of the GSCs, from the raw material suppliers to the final assemblers, taking the activities of the service providers into consideration. The relation between the final assemblers and customers is beyond the scope of this paper.

Indices used in the mathematical formulations are the following:

- *i*- Product identifier; *j*- supplier identifier (primary, secondary, raw material, etc. suppliers); *k*- final assembler identifier; *l*- customer identifier; *m*- service provider identifier; *t*- time interval; *FA*: final assembler; *S*: supplier; and *SP*: service provider.

3.1.1. Total Cost Objective Function

The total cost of the GSCs, including the production costs, raw material costs, component costs, transportation costs, inventory costs, and costs of service providers (Equations (2)–(6)).

$$f_1 = CP + CM + CT + CI + CS. \tag{1}$$

- *Total production cost*: The summation of manufacturing costs at *Ss* and *FAs*, as follows:

$$CP = \sum_t \sum_j \sum_i cp_{ij} Q_{ijt} + \sum_t \sum_k \sum_i cp_{ik} Q_{ikt}, \tag{2}$$

  where cp_{ij} is the unit production cost of parts of final product i at Ss; cp_{ik} is the unit production cost of final product i at FAs; Q_{ijt} is the production quantity of parts of final product i at Ss during time period t; and Q_{ikt} is the production quantity of final product i at FAs during time period t.
- *Total cost of raw materials and parts* is the summation of material costs at *Ss* and *FAs*, as follows:

$$CM = \sum_t \sum_j \sum_i cm_{ij} Q_{ijt} + \sum_t \sum_k \sum_i cm_{ik} Q_{ikt}, \tag{3}$$

  where cm_{ij}, cm_{ik} are the unit material costs and Q_{ijt}, Q_{ikt} are the production quantities.
- *Transportation cost* is the summation of cost of transportation between the manufacturing companies of the supply chain (between Ss; between Ss and FAs), as follows:

$$CT = \sum_t \sum_k \sum_j \sum_i ct_{ijk} Q_{ijkt} + \sum_t \sum_l \sum_k \sum_i ct_{ikl} Q_{iklt}, \tag{4}$$

  where ct_{ijk}, ct_{ikl} are the unit transportation costs; and Q_{ijkt}, Q_{iklt} are the volumes of goods.

- *Inventory cost* is the summation of inventory costs at manufacturing companies of the supply chains (at *S*s and *FA*s) as follows:

$$CI = \sum_t \sum_j \sum_i ci_{ij} I_{ijt} + \sum_t \sum_k \sum_i ci_{ik} I_{ikt}, \tag{5}$$

  where ci_{ij}, ci_{ik} are the unit inventory costs; and I_{ijt}, I_{ikt} are the volumes of goods to be stored.
- *Cost of service activities at service providers* (e.g., packaging, labelling, documentation, financing, etc.), as follows:

$$CS = \sum_t \sum_m \sum_i Csp_{imt}, \tag{6}$$

  where Csp_{imt} is the cost of activities of *SP*s needed for production of final product *i*.

3.1.2. Total Lead Time Objective Function

The total lead time of the GSCs, including the production lead times at *S*s and *FA*s, the lead times of services at *SP*s, the lead times of warehousing, and the lead times of transportation (Equations (8)–(11)) as follows:

$$f_2 = TP + TS + TW + TT. \tag{7}$$

- *Total production lead time* is the summation of manufacturing lead times at production enterprises of the supply chains (*S*s and *FA*s), as follows:

$$TP = \sum_t \sum_j \sum_i tp_{ij} Q_{ijt} + \sum_t \sum_k \sum_i tp_{ik} Q_{ikt}, \tag{8}$$

  where tp_{ij}, tp_{ik} are unit production lead times; and Q_{ijt}, Q_{ikt} are production quantities.
- *Total service lead time* is the summation of time consumptions of activities of service providers of the supply chains required for manufacturing (packaging, labeling, etc.), as follows:

$$TS = \sum_t \sum_m \sum_i Tsp_{imt}. \tag{9}$$

- *Total warehousing time* is the summation of the storage times at the members of the supply chains (*S*s, *FA*s and *SP*s), as follows:

$$TW = \sum_j \sum_i tw_{ij} + \sum_k \sum_i tw_{ik} + \sum_m \sum_i tw_{im}. \tag{10}$$

- *Total transport time* is the sum of transportation times of loading units, between *S*s and *FA*s, as follows:

$$TT = \sum_k \sum_j \sum_i tt_{ijk}. \tag{11}$$

3.2. Design Constraints

During the single- and multi-objective optimization the following 4 design constraints were defined: (1.) Constraints for production and service capacities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain's members, and (4.) constraints for the sustainability of the chain's members.

3.2.1. Production and Service Capacity Constraints

Limitations have to be defined for the minimal volume of the production at production companies of the GSCs (*S*s and *FA*s), as follows:

$$Q_{ijt}^{\min} \leq Q_{ijt}, \tag{12}$$

$$Q_{ikt}^{\min} \leq Q_{ikt}. \tag{13}$$

Limitations have to be defined for the minimal volume of the service capacities at service providers of the GSCs (*SP*s), as follows:

$$Q_{imt}^{\min} \leq Q_{imt}. \tag{14}$$

The minimum values of capacities relating to the chain's members provide the continuous operation of the GSCs.

3.2.2. Inventory Constraints

The volume of inventories has to be limited at production companies and service providers of the GSCs (*S*s, *FA*s and *SP*s), as follows:

$$I_{ijt}^{\min} \leq I_{ijt} \leq I_{ijt}^{\max}; I_{ikt}^{\min} \leq I_{ikt} \leq I_{ikt}^{\max}; I_{imt}^{\min} \leq I_{imt} \leq I_{imt}^{\max}. \tag{15}$$

The minimum values of the inventories provide the continuous operation of the GSCs, the maximum values provide that the loss will be minimized in the chains (the stock is a typical type of waste according to lean philosophy).

3.2.3. Flexibility Constraints

Responsiveness and flexibility of the companies have become key characteristics for being profitable. Supply chains adapt to the rapidly changing market demands if they are flexible, so flexibility is essential to increase or maintain competitiveness. Chan et al. [15] gave definitions and characteristics for the following flexibilities: Manufacturing flexibility, strategic flexibility, resource flexibility, coordination flexibility, range flexibility, and response flexibility.

In our conception the following flexibility constraints are defined for the chain's members:

- *Flexibility of the manufacturing system* at the manufacturing companies (capability for producing high variety of goods in type and volume continuously) (*FA* and *S*s), as follows:

$$FL_{ijt}^{\min} \leq FL_{ijt}, \tag{16}$$

$$FL_{ikt}^{\min} \leq FL_{ikt}. \tag{17}$$

- *Flexibility of the service providers* (capability for providing continuous, reliable, high quality and high variety of services in type and volume) (*SP*s), as follows:

$$FL_{imt}^{\min} \leq FL_{imt}. \tag{18}$$

- *Financial liquidity* of all of the chain's members (high flexibility requires investment), as follows:

$$LI_{ijt}^{\min} \leq LI_{ijt}; LI_{ikt}^{\min} \leq LI_{ikt}; LI_{imt}^{\min} \leq LI_{imt}. \tag{19}$$

The flexibility constraints can be given by a value in a given interval (1–5) based on a complex evaluation. These values are also taken into consideration in the software application.

3.2.4. Sustainability Constraints

Sustainability performance measurement and evaluation of the production companies and service providers is a complex task. Key Performance Indicators (KPI) are efficient tools for performance measurement of production and logistics activities. KPIs provide high transparency of the processes, since processes that can be measured can be improved. In our conception, the sustainability requirements are taken into consideration in all of the three aspects, environmental, social, and economic, according to the most of the relevant publications in recent literature. Based on these issues the sustainability of all companies can be evaluated by KPIs. In the literature there are a lot of suggestions for the performance measurement of the sustainability. Ad J. de Ron offered the following issues for the performance measurement of sustainability: Cost awareness, process quality, product quality, energy usage, recovery rate, and life cycle performance [49].

In practice, the most often applied KPIs, according to the literature, are the following: e.g., The ratio of material recycling and reuse; the amount of material usage (raw materials, components); the ratio of advanced materials; the ratio of energy- and material-efficient final products; the ratio of renewable energy; the ratio of energy-efficient production technologies; the utilization of resources; energy consumption; energy saving; amount of emissions; the product recycling rate; waste reduction rate; waste recycling rate; amount of hazardous substances/chemicals; volume of noise and vibration; measurement of safety and health of workers; worker satisfaction; and training and career development programs [34,40–42].

In the developed method and software, the following sustainability constraints are defined for the chain's members:

- *Sustainability of the manufacturing companies* of the global supply chains (*FA* and *S*s), as follows:

$$SS_{ijt}^{\min} \leq SS_{ijt}, \tag{20}$$

$$SS_{ikt}^{\min} \leq SS_{ikt}. \tag{21}$$

- *Sustainability of the service providers* of the global supply chains (*SP*s), as follows:

$$SS_{imt}^{\min} \leq SS_{imt}. \tag{22}$$

The sustainability constraints can be given by a value in a given interval (1–5) based on a complex evaluation. These values are also taken into consideration in the software application.

3.3. Optimization Method

The single-objective optimization (cost or lead time objective functions) is achieved by the systematic search method.

The elaborated multi-objective formulation takes Equations (1) and (7) as the objective functions, f_1 and f_2. The multi-objective optimization problem can be expressed as follows:

$$\min_{x \in Q} \{f_1(x), f_2(x)\}, \tag{23}$$

where x is the vector of decision variable and Q is the space of feasible solutions.

The multi-objective optimization is performed by the systematic search method. The normalized weighting method is also applied to analyze the weights (ratio) of the objective functions (cost and lead time) in the optimization.

$$f(x) = \sum_{\alpha=1}^{2} w_\alpha f_\alpha(x)/f_\alpha^0 \text{ where } w_\alpha \geq 0 \text{ and } \sum_{\alpha=1}^{2} w_\alpha = 1, \tag{24}$$

where $f_\alpha(x)$ are the objective functions and w_α are the weights of the objective functions. The condition $f_i^0 \neq 0$ is assumed.

In case of the multi-objective optimization due to the weighting method, depending on the design strategy (type of final product; customers' requirements; location of the customers; life standard of the customers; type of industrial sector; competitors' products; etc.) the manager has to define whether the minimization of the cost or the lead time is the more important design aim. Therefore, the ratio of the objective functions must also be given.

3.4. Software for Optimization of Sustainable Global Supply Chains

Software has been developed based on the elaborated optimization method, which can be applied for the optimization of profitable and sustainable GSCs. The software has been developed in the Java programming language.

Introduction of the Software Conception

- *The process of the optimization* can be seen in Figure 3, according to the software main screen of the Figure 4.
- The main screen of the developed software application can be seen in Figure 4.

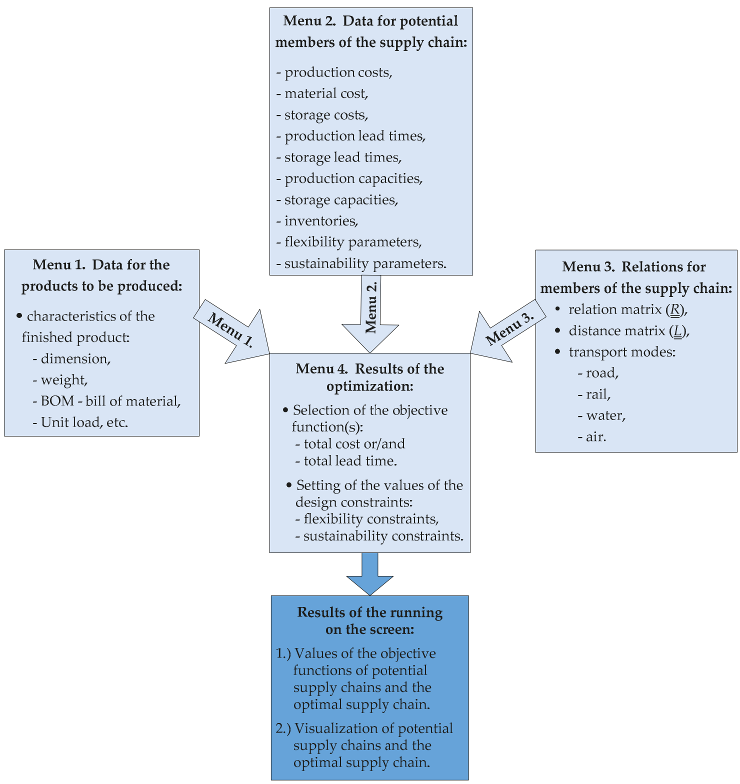

Figure 3. Process of the optimization based on the software screen. Source: Own.

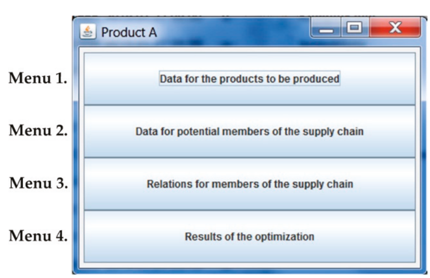

Figure 4. Main screen of the software.

4. Discussion—Main Significant Added Value of Our Developed Optimizing Method and Decision Supporting Software—Confirmed by a Real Case Study

The main aims of the research were the following:

- The primary goal was to develop an optimization method and software which provides the creation of optimal GSCs' networks that are not only cost-effective and time-effective, but at the same time sustainable. With the software only optimal sustainable GSCs can be created, since sustainability, as a design constraint, is built into the method and software.
- Another aim was to ensure that different optimal combinations of GSCs can be formed from the same potential suppliers and service providers, even in case of different ratios of the objective functions (cost, lead time). The ratio of the objective functions can be set arbitrarily in the software depending on the design strategy (type of final product; customers' requirements; location of the customers; living standard of the customers; type of industrial sector; competitors' products; etc.) of the GSC management. If the management's strategic aim is to minimize the total cost of the GSC, the ratio of the cost objective function will be higher than the lead time objective function. It is often used if the most important aspect for the customers is the low cost of the products (e.g., the final products are traditional basic commodities; the customers are cost-sensitive due to their living standard or their location). However, if the customers are not especially cost-sensitive and the most important requirement is, rather, the shortest delivery time (total lead time), then the ratio of the lead time objective function will be higher. This strategy is used in cases including the fashion industry, high-tech products, and luxury products, whose portfolio changes very quickly due to their short life cycle. Thus, the sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions because the sustainability design constraints are built into the method and the software.
- A further aim of the study was to use a real case study to confirm that the developed optimization method and software can achieve the two before-mentioned aims, i.e., the software can be applied effectively in practice for the optimization of sustainable GSCs.

4.1. Main Significant Added Value of Our Developed Optimizing Method and Decision Supporting Software Compared to Other Optimizing Methods and Software Applications

Although the existing literature often discusses the design of supply chains, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods which can be found in the existing literature use a limited number of design constraints. The sustainability design constraint is not taken into consideration at all during the optimization. Only a few publications refer to the flexibility design constraint, but in these articles the meaning of flexibility is not discussed in enough detail. Therefore, our developed method and software make a novel contribution to the recent state of the research field, as it is the first time in the literature that sustainability and flexibility design constraints are taken into consideration simultaneously. This means that during the optimization the potential supply chain members have been analyzed regarding their fulfillment of sustainability and flexibility requirements.

- During optimization the sustainability design constraints are taken into consideration and built into the method and software, in addition to the generally applied design constraints (e.g., production and service capacities, limitations for the volume of inventories, etc.). The potential suppliers and service providers can only be members of a sustainable GSC if these companies fulfill the sustainability requirements. Both the sustainability of the production companies and the sustainability of the service providers are analyzed and evaluated. Since all of the members of the GSC have to fulfill the sustainability constraints, by applying the software an optimal GSC can be formed which is not only cost- and time-effective and profitable (as in the case of the other optimizing software) but, at the same time, also sustainable. In the literature this is the first time the potential supply chain members' ability to fulfill the sustainability requirements has been analyzed.

- Depending on the design strategy (type of final product; customers' requirements; location of the customers; living standard of the customers; type of industrial sector; competitors' products, etc.) of the GSC management, the ratio of the cost and lead time objective functions can be set arbitrarily in the software. Therefore, with the software, an optimal sustainable GSC can be formed according to the individual demand of the final assembler. Depending on the ratio of the objective functions the optimal combinations of the sustainable GSC members will differ. The most important advantage of our method and software is that the sustainability of the optimal GSCs can be provided in case of every kind of ratio of the objective functions because the sustainability design constraints are built into the software.
- During the optimization the flexibility design constraints are also taken into consideration in the method and built into the software. Flexibility means the capability of the supply chain members for adapting to changing customer and market demands. Flexibility design constraints are the following: (1) Constraint for the flexibility of the manufacturing systems (machines, technologies, etc.) at production companies, (2) flexibility constraint for the service providers (primarily focusing on forwarding enterprises, which are the most expensive and environmentally damaging service providers) and (3) financial liquidity constraint for the production companies and service providers. The flexibility includes the following: Resource flexibility, flexibility of the organization structure, strategic flexibility, and flexibility for collaboration between manufacturing enterprises, service providers, and stakeholders.
- The software provides the opportunity to select the required transport modes (road, rail, air, and water) in all relations between the potential suppliers and between the potential suppliers and the final assembler of GSCs. Consequently, the sustainable transport chains can be configured preferring environmentally friendly transport modes (water, rail) to minimize environmental damage, noise, and air pollution in the GSCs by the selection of the optimal service providers (transport companies).
- Our developed software is user friendly, easy to use, and customizable based on user demands.

4.2. Positive Effects of the Application of the Our Developed Method and Decision Supporting Software on the Sustainable GSCs' Operation

- The method and the software support the decision making of the management in the formation and analysis of the potential GSC alternatives and analyze the ability of the potential manufacturing companies (suppliers) and service providers to fulfill all of the design constraints, involving sustainability requirements as well.
- The method and the software support the decision making of the management in the selection of the optimal GSC (involving optimal suppliers and service providers) after the evaluation of the GSC alternatives.
- The software supports the analysis and evaluation of the different shoring and sourcing strategies (e.g., offshoring, outsourcing, offshore outsourcing, reshoring, etc.). The potential chain members and their parameters and the distances between the members and the applied transport modes (rail, road, water, air) can be given arbitrarily in the software. During the optimization, based on the before-mentioned input data, the optimal partners can be selected at the same time taking into consideration the positive and negative effects of different shoring and sourcing strategies on the GSCs' sustainability [50].
- The method and the software provide the formation of long-term strategic partnerships between the GSC's members and the long-term predictability of the sustainable GSC.
- The risks and losses are minimized in the sustainable GSC.
- The stakeholders' and customers' satisfaction increases.

- The method and the software provide fast reconfiguration of the GSC in case of the changing of the parameters (input data) by the members.
- The profit at all of the GSC's members is maximized.

4.3. Real Case Study for Optimization of a Sustainable Global Supply Chain

In this section a real case study is introduced for the optimal design of a sustainable GSC by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from several potential suppliers and service providers.

Three optimal GSCs are searched in the case study for three cases as follows: (1.) Total cost minimization of the GSC (single-objective cost optimization); (2.) total lead time minimization of the GSC (single-objective lead time optimization); and (3.) a different ratio of the objective functions (multi-objective cost-lead time optimization: 60% cost–40% lead time).

4.3.1. Problem Description

The goal is the formation of an optimal sustainable GSC of a final assembler (FA). The potential members of the chain are 4 potential primary suppliers (S_{11}, S_{12}, S_{13}, S_{14}); 5 potential secondary suppliers (S_{21}, S_{22}, S_{23}, S_{24}, S_{25}); and 3 potential forwarding service providers (SP_1, SP_2, SP_3) (Figure 5).

One optimal primary supplier, one optimal secondary supplier, and one optimal forwarding service provider have to be selected to form the optimal sustainable GSC.

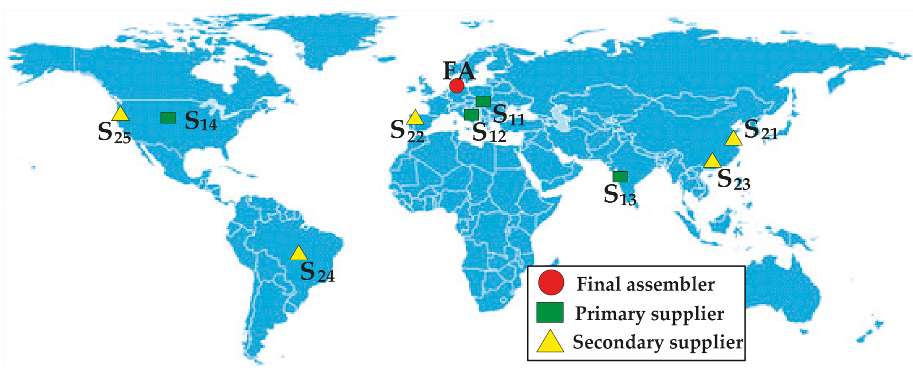

Figure 5. Potential primary and secondary suppliers of the sustainable GSC. Source: Own.

4.3.2. Input Data for the Calculation

Relation Matrix

Relations of the final assembler, potential primary suppliers, potential secondary suppliers, and potential service providers can be given by a relation matrix ($\underline{\underline{R}}$), as follows:

$$\underline{\underline{R}} = \begin{array}{c} \\ 1 \\ \vdots \\ \\ \vdots \\ n \end{array} \begin{array}{c} 1 \quad \ldots \qquad \ldots \quad n \\ \begin{bmatrix} & & \\ & & \\ & 1/0 & \\ & & \\ & & \end{bmatrix} \end{array}$$

- *n:* identifiers of final assembler, potential suppliers and potential service providers,
- value of elements of the matrix is 0 (there isn't relation between members) or 1 (there is relation between members).

Table 1 shows the relation matrix of the members of the GSC.

Table 1. Relation matrix of the global supply chain's members.

	FA	**S_{11}**	**S_{12}**	**S_{13}**	**S_{14}**	**S_{21}**	**S_{22}**	**S_{23}**	**S_{24}**	**S_{25}**	**SP_1**	**SP_2**	**SP_3**
FA	0	1	1	1	1	0	0	0	0	0	1	1	1
S_{11}	1	0	0	0	0	1	0	0	1	1	1	1	1
S_{12}	1	0	0	0	0	1	0	1	0	1	1	1	1
S_{13}	1	0	0	0	0	0	1	0	1	0	1	1	1
S_{14}	1	0	0	0	0	1	0	0	0	1	1	1	1
S_{21}	0	1	1	0	1	0	0	0	0	0	1	1	1
S_{22}	0	0	0	1	0	0	0	0	0	0	1	1	1
S_{23}	0	0	1	0	0	0	0	0	0	0	1	1	1
S_{24}	0	1	0	1	0	0	0	0	0	0	1	1	1
S_{25}	0	1	1	0	1	0	0	0	0	0	0	0	0
SP_1	1	1	1	1	1	1	1	1	1	1	0	0	0
SP_2	1	1	1	1	1	1	1	1	1	1	0	0	0
SP_3	1	1	1	1	1	1	1	1	1	1	0	0	0

Distance Matrix

The distances between the final assembler and potential suppliers can be given by the following matrix ($\underline{\underline{L}}$).

$$\underline{\underline{L}} = \begin{array}{c} \\ 1 \\ \vdots \\ \vdots \\ n \end{array} \overset{\begin{array}{cccc} 1 & \ldots & \ldots & n \end{array}}{\begin{bmatrix} & & & \\ & & & \\ & & & \\ & & & \end{bmatrix}}$$

- elements of the matrix are the transport distances between the members of the GSC [km].

Table 2 shows the distance matrix of the members of the global supply chain.

Table 2. Distance matrix [Km].

	FA	**S_{11}**	**S_{12}**	**S_{13}**	**S_{14}**	**S_{21}**	**S_{22}**	**S_{23}**	**S_{24}**	**S_{25}**
FA	0	963	1234	12,611	11,395	19,925	12,660	18,565	11,879	15,553
S_{11}	963	0	1216	8885	15,936	16,188	2523	14,880	12,719	17,735
S_{12}	1234	1216	0	7928	12,520	15,723	1956	15,256	10,921	15,937
S_{13}	12,611	8885	7928	0	20,029	8562	9115	7255	15,859	18,152
S_{14}	11,395	15,936	12,520	20,029	0	19,798	11,075	20,911	12,469	2908
S_{21}	19,925	16,188	15,723	8562	19,798	0	16,766	1527	21,612	10,032
S_{22}	12,660	2523	1956	9115	11,075	16,766	0	15,412	10,489	15,243
S_{23}	18,565	14,880	15,256	7255	20,911	1527	15,412	0	20,317	11,208
S_{24}	11,879	12,719	10,921	15,859	12,469	21,612	10,489	20,317	0	15,618
S_{25}	15,553	17,735	15,937	18,152	2908	10,032	15,243	11,208	15,618	0

Further Input Data for the Calculations

Table 3 shows the data relating to the final assembler, potential primary suppliers, potential secondary suppliers, and potential service suppliers. Table 3 includes the unit production costs, the unit material costs, the unit production lead times, the maximal production capacities, and the maximal storage capacities at the final assembler and at the potential suppliers, furthermore the flexibility, the liquidity, and the sustainability parameters of the final assembler, the potential suppliers, and the potential service providers.

The specific transportation cost (c_t) in the case of road transport is 0.00024 Eur/piece/Km, in the case of water transport is 0.00012 Eur/piece/Km, in the case of rail is 0.00016 Eur/piece/Km, and in the case of air transport is 0.00058 Eur/piece/Km.

Table 3. Input data for the calculation.

	Unit Production Cost $cp_{j,k}$ [Eur/pieces]	Unit Manufacturing Cost $cm_{j,k}$[Eur/pieces]	Unit Production Lead Time $tp_{j,k}$ [hour]	Unit Production Capacity $Q_{j,k}$ [pieces/week]	Storage Capacity at the Member $I_{j,k}$ [unit load]	Flexibility of the Member $FL_{j,k,m}$	Liquidity $LI_{j,k,m}$	Sustainability of the Member $SS_{j,k,m}$
FA	120	80	30	4500	7000	5	3	4
S_{11}	50	50	10	2500	4000	3	3	5
S_{12}	50	40	12	2500	3500	4	3	5
S_{13}	28	30	10	2500	5000	3	5	4
S_{14}	35	15	8	3500	4000	5	3	4
S_{21}	28	15	10	2000	5500	4	3	4
S_{22}	55	17	4.5	900	4500	3	3	3
S_{23}	16	7	14	2500	4500	4	3	4
S_{24}	25	16	12	1500	5000	3	3	4
S_{25}	45	24	17	1100	3500	3	3	3
SP_1	-	-	-	-	-	5	4	4
SP_2	-	-	-	-	-	5	4	5
SP_3	-	-	-	-	-	4	4	3

4.3.3. Run of the Optimization Software

At first the input data of the case study have to be given according to the Menu 1–3 of the main screen (Figure 4). After that, the objective function(s) have to be selected and the minimal values of the design constraints and the production volume have to be given in the Menu 4. (Figure 4).

Input Data Given

1. *Data for the products to be produced* (Menu 1.): the characteristics of the finished product have to be given:
    - Dimension of the final product,
    - BOM (bill of material),
    - unit load dimensions and weights.
2. *Data for potential members of the supply chain* (Menu 2.): The unit production costs, the unit material costs, the unit production lead times, the maximal production capacities, and the maximal storage capacities at the final assembler and at the potential suppliers, furthermore, the flexibility, the financial liquidity, and the sustainability parameters of the final assembler, the potential suppliers, and the potential service providers have to be given according to the data of Table 3.
3. *Relations for members of the supply chain* (Menu 3.—Figures 6 and 7): The relation matrix (Table 1), the distance matrix (Table 2), and the transport modes (road, rail, air, and water) applied for the transportation of goods between all of the relations have to be given.

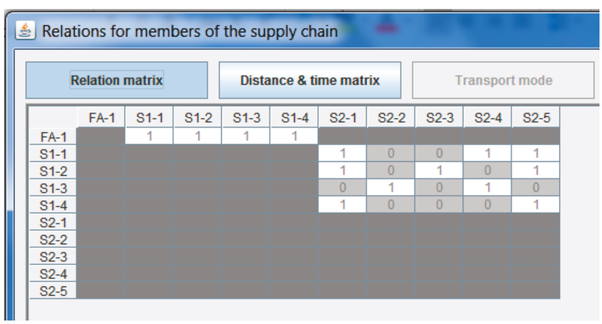

Figure 6. Parameter setting of the relation matrix.

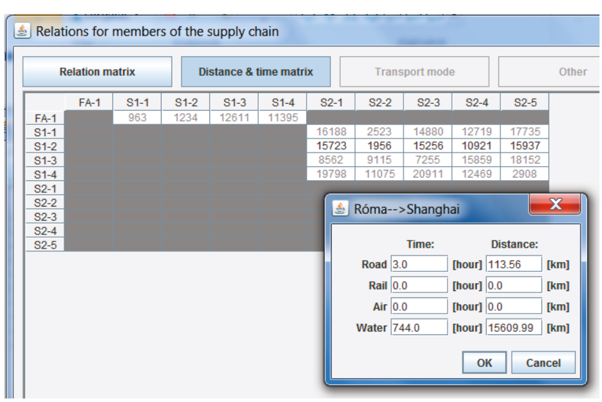

Figure 7. Given elements of the distance matrix.

The software also provides the possibility of precise determination (distances and transit times) of the transport modes (road, rail, air, and water) in all relations between the potential suppliers and between the potential suppliers and the final assembler (Figure 7).

There is a very good opportunity to configure sustainable transport chains preferring environmentally friendly transport modes (water, rail) to minimize environmental damage, noise, and air pollution in the GSCs.

4.3.4. Run Results of the Optimization Software

Results of the optimization (Menu 4.—Figure 8): The total cost or/and total lead time objective function(s) (Equations (1) and (7)) can be selected.

In case of the multi-objective optimization due to the weighting method, which depends on the preferred design aim, the weights of the objective functions can be set arbitrarily (in the case study cost: 60%—lead time: 40%). In this study, at first the single-objective optimization than the multi-objective optimization will be shown.

The minimal values for the design constraints (Equations (12)–(14) and (16)–(22)) can also be set by the supply chain manager in this menu (Figure 8), as follows: Our project includes the flexibility of the production companies (value: 3), the flexibility of the service providers (value: 4), the liquidity of all of the companies (value: 3), the sustainability of the manufacturing companies (value: 4), and the sustainability of the service providers (value: 4).

The production volume also has to be given (in 1000 units of final products).

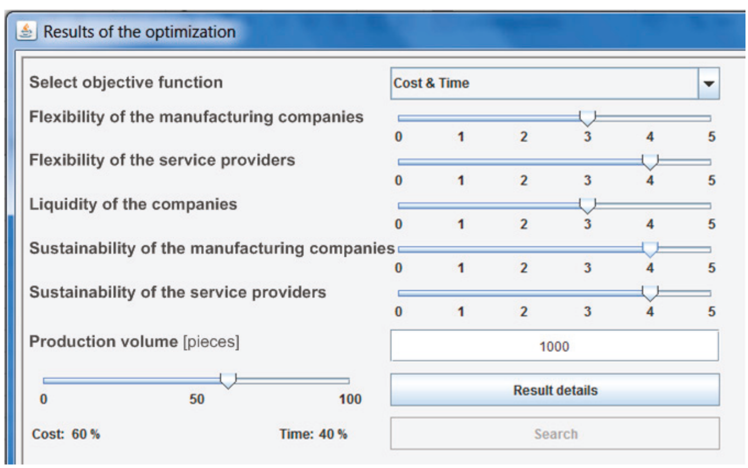

Figure 8. Selection of the objective function(s) and setting of the values for the design constraints.

5. Results of the Single- and Multi-Objective Optimizations of the Sustainable Global Supply Chains

In this section the results of the optimization are described. Three optimal sustainable GSCs have been searched for three cases, as follows: (1.) Total cost minimization of the GSC (single-objective cost optimization); (2.) total lead time minimization of the GSC (single-objective lead time optimization); and (3.) a different ratio of the objective functions (multi-objective cost-lead time optimization: 60% cost–40% lead time).

5.1. Single-Objective Cost Optimization—The Optimal Sustainable Global Supply Chain

Figure 9 shows the result of the optimization for minimal cost. The possible six GSCs that fulfill all of the design constraints are listed on the right side of the print screen. These GSC alternatives are also visualized graphically in Figure 9.

Supplier S_{25} and service provider SP_3 cannot fulfill the sustainability requirements, while supplier S_{22} cannot fulfill either the sustainability constraint or the production capacity constraint. Therefore, these three companies are not eligible to be members of the GSC.

The optimal sustainable GSC formation, which provides the minimal total cost in our case study, is the following: **FA –** $\mathbf{S_{14}}$ **–** $\mathbf{S_{21}}$ (colored in green in Figure 9). The total cost of the final product is 297 EUR/unit in the optimal GSC.

The optimal forwarding company is the $\mathbf{SP_2}$ which provides the most cost effective and sustainable transportation in the optimal GSC between FA – S_{14} – S_{21}.

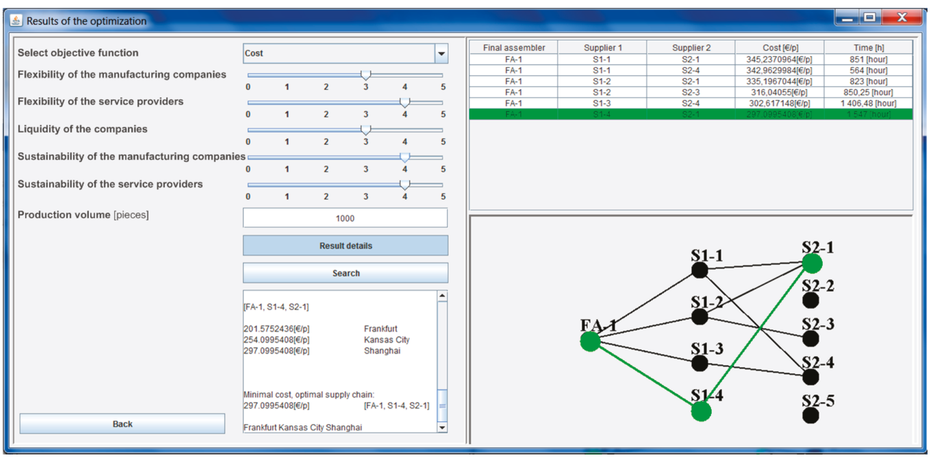

Figure 9. Optimal sustainable GSC in case of single-objective cost optimization.

5.2. Single-Objective Lead Time Optimization—The Optimal Sustainable Global Supply Chain

Figure 10 shows the result of the optimization for minimal lead time. The possible six GSCs that fulfill all of the design constraints are listed on the right side of the print screen. These GSC alternatives are also visualized graphically in Figure 10.

Supplier S_{25} and service provider SP_3 cannot fulfill the sustainability requirements, while supplier S_{22} cannot fulfill either the sustainability constraint or the production capacity constraint. Therefore, these three companies are not eligible to be members of the GSC.

The optimal sustainable GSC formation which provides the minimal total lead time in our case study is the following: **FA –** $\mathbf{S_{11}}$ **–** $\mathbf{S_{24}}$ (colored in green in Figure 10). The total lead time of one piece of a final product is 564 [hour] in case of the optimal GSC.

The optimal forwarding company is the $\mathbf{SP_2}$, which provides the most time effective and sustainable transportation in the optimal GSC between FA – S_{11} – S_{24}.

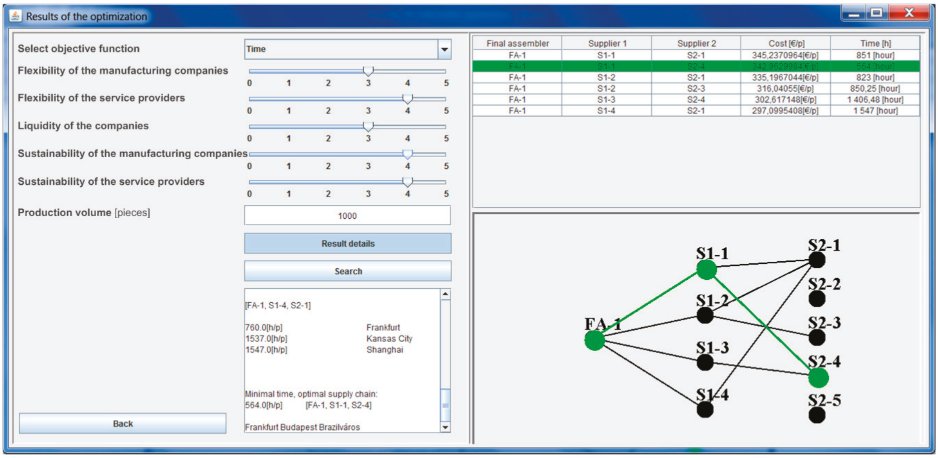

Figure 10. Optimal sustainable GSC in case of single-objective lead time optimization.

5.3. Multi-Objective Optimization—Optimal Sustainable Global Supply Chain

The software application provides the possibility for multi-objective optimization (total cost, total lead time). During multi-objective optimization, the systematic search method, combined with a normalized weighting method, was applied to analyze the weights (ratio) of the objective functions.

In case of the multi-objective optimization, depending on the design strategy (type of final product; customers' requirements; location of the customers; life standard of the customers; type of industrial sector; competitors' products; etc.) the GSC manager has to define the more preferred design aim and the ratio of the cost objective function and lead time objective function.

In the case study, the ratio of the objective functions was defined as follows: 60% cost–40% lead time. The result of the multi-objective optimization can be seen in Figure 11. The optimal sustainable GSC formation which provides a 60% cost–40% lead time ratio of objective functions in the case study is the following: $\mathbf{FA - S_{12} - S_{23}}$ (in Figure 11 colored by green).

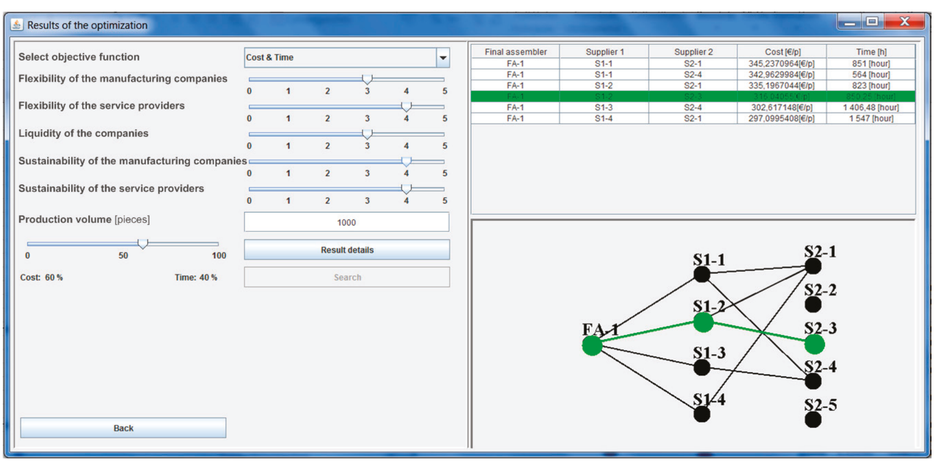

Figure 11. Optimal sustainable GSC in case of multi-objective cost—lead time optimization.

The optimal forwarding company is the $\mathbf{SP_2}$, which provides the required cost–time effective and sustainable transportation in the optimal GSC between $FA - S_{12} - S_{23}$.

5.4. Summary of the Optimization Results

From the case study the following results can be summarized:

- In case of different ratios of the objective functions (cost, lead time) different optimal combinations of sustainable GSCs can be formed from the same potential suppliers and service providers (Figures 9–11). The ratio of the objective functions depends on the design strategy (type of final product; customers' requirements; location of the customers; living standard of the customers; type of industrial sector; competitors' products; etc.) of the GSC management.
- The sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions, because the sustainability design constraints for manufacturing companies and service providers are built into the method and the software. Therefore, all of the three above-described optimal GSCs are sustainable.
- In all three cases the same forwarding company was selected as the optimal service provider providing the most sustainable services. Thus, environmental damage, noise, and air pollution were minimized in the sustainable GSCs.

6. Conclusions, Limitations and Future Research

Presently, in production, the resources are limited, there is an increasing human population, market competition, and environmental damage, therefore current practices in the use of resources are not sustainable. New innovative and environmentally friendly technologies, efficiency improvement, and the optimization of production and logistical processes are required. The production companies have to establish not only cost-effective and profitable, but at the same time, sustainable production.

The optimization of sustainable GSCs is an important and essential tool for optimal formation and operation of efficient, profitable, and sustainable GSC networks.

In the study a single- and multi-objective optimization method was elaborated for the optimal design of sustainable GSC networks, which provides the creation of the optimal combination of sustainable GSCs' members to achieve not only cost-effective and time-effective, but at the same time, sustainable operation. During the optimization the objective functions of (1.) total cost and/or (2.) lead time and the four design constraints, (1.) capacity constraints for production and service activities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain's members, and (4.) constraints for the sustainability of the chain members, are considered.

The systematic search method was used for single-objective optimization, while the multi-objective optimization was performed by the systematic search method combined with the normalized weighting method. In the case of multi-objective optimization, due to the weighting method and depending on the design strategy, the GSC management has to define the ratio of the cost objective function and lead time objective function.

Software has been developed based on the elaborated optimization method. With the software a sustainable optimal GSC can be formed according to the individual demand of the final assembler. Due to the normalized weighting method, the weights of the objective functions have to be set arbitrarily in the software.

Our developed method and software are an additional contribution to the recent state of the research field because it is the first of the literature to take sustainability and flexibility design constraints into consideration simultaneously and build them into the method and software.

Flexibility constraint means the capability of the chain members to adapt to changing market demands. Flexibility and financial liquidity of the GSCs' members are analyzed and evaluated. The flexibility includes the following: Resource flexibility; flexibility of the organization structure; strategic flexibility; and flexibility for collaboration between production companies and service providers.

Sustainability design constraint means that the potential suppliers and service providers can only be members of an optimal sustainable GSC if these companies fulfill the sustainability requirements. Since all of the members of the GSC have to fulfill the sustainability constraints, by applying the software, an optimal GSC can be formed which is not only cost- and time-effective (as in case of the other optimizing software) but at the same time sustainable.

A real case study was introduced to confirm that our developed optimization method and software can be applied effectively in practice for the optimization of sustainable GSCs. In a case study, the optimal design of a sustainable GSC was described by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from more potential suppliers and service providers for three cases, as follows: (1.) Total cost minimization of the GSC; (2.) total lead time minimization of the GSC; and (3.) in case of different ratio of the objective functions (60% cost–40% lead time). It can be concluded that, depending on the ratio of the objective functions, the optimal combinations of the sustainable GSC′ members are different (Figures 9–11).

It can be summarized that our developed method and software are an additional contribution to the recent state of the research field, because, by the application of the software, only sustainable optimal GSCs can be created, in case of every kind of ratio of the objective functions, since sustainability as a design constraint is built into the method and software.

The limitation of our developed software is that, among the activities of the service providers, only the activities of transport service providers have been taken into consideration during the calculation of total cost and total lead time of the GSC, as transportation is the most environmentally damaging and expensive activity in sustainable GSCs. Further service providers would be taken into account in the future to define the total costs and lead times of the GSCs more precisely.

The research introduced in the recent article can be continued by the development of optimization methods and software applications which are specialized for the optimization of sustainable GSCs of different industrial sectors requiring other objective functions or, further, more specific design constraints.

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Appendix A

The manufacturing practices relating to the nine principles of sustainable production are the following: (In the Section 2.2.1. Sustainable Production in the Global Supply Chain) [37–40].

1. Sustainable design of products
    - Practical tools for sustainable production [40]:
        - Application of advanced materials and innovative and green production technologies; design of energy, material, and cost-efficient products;
        - hazardous substances substitution or elimination in products and processes;
        - considerations regarding disassembly, reuse, and recycling during product design;
        - eco-design assisted by customers;
        - recyclability and reuse of incoming materials packaging and packaging minimization.
2. Energy and materials efficiency during the manufacturing of products
    - Practical tools for sustainable production [40]:
        - Mapping energy consumption for identifying energy saving possibilities;
        - use of renewable energy; application of energy-efficient manufacturing systems;

    - equipment upgrades for improving efficiency; preventive equipment maintenance;
    - employee training on energy savings; energy audits;
    - material recycle and reuse; material substitution for better efficiency;
    - material usage optimization; process optimization.

3. Substitution or elimination of hazardous materials and technologies in manufacturing processes

  - Practical tools for sustainable production [40]:

    - Hazardous substances substitution or elimination in production processes;
    - tracking chemicals in processes and products; heavy metals filtration;
    - training of workers on hazardous substances;
    - application of closed-loop process water systems.

4. Elimination or recycling of wastes

  - Practical tools for sustainable production [40]:

    - Component and product design optimization; substitution of hazardous materials;
    - redesigning of components to reduce solid waste; non-conforming products reduction;
    - reuse and recycle of direct and indirect waste; external and internal recycling;
    - donation of waste and by-products to other industries or institutions.

5. Establish safe workplaces and technologies

  - Practical tools for sustainable production [40]:

    - Robotic automation in hazardous activities; mechanical lifting aids;
    - internal safety inspections; external work environment audits;
    - employee rotation among work stations; employee training on hazardous risks;
    - process modifications to reduce noise and vibration.

6. Management activity for continuous evaluation and improvement of processes from economic, environment, and safety aspects

  - Practical tools for sustainable production [40]:

    - Strategic sustainability and functional goals are displayed throughout the plant;
    - technology investment prioritization considering environment, safety, quality, and economic aspects; communicating with employees about strategic plans, targets, and results;
    - ISO 9001 for continuous managerial evaluation.

7. Motivation of employees in order to improve the efficiency and creativity

  - Practical tools for sustainable production [40]:

    - Work standardization; work accountability;
    - employee improvement suggestions goals; team work; improvement meetings;
    - rewards for applicable improvement suggestions from employees.

8. Social advantages and advancement possibilities for employees

  - Practical tools for sustainable production [40]:

- Health and safety management system; employee rotation;
- training plans; career development programs; job satisfaction assessment;
- scholarships; subsidies for health and well-being purposes;
- performance appraisal; ISO 9001 supporting training and competence.

9. Development of community-company partnership

- Practical tools for sustainable production [40]:
    - Job opportunities for locals; collaboration with educational institutions;
    - periodical meetings with local authorities; volunteer work within local communities.

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Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability

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Abstract: Nowadays, Lean Manufacturing, Industry 4.0, and Sustainability are important concerns for the companies and in a general way for the society, principally, the influence of the two production philosophies, Lean Manufacturing and Industry 4.0, in the three main pillars of sustainability: economic, environmental, and social. According to the literature review done in this work, these relations are not well known and are dispersed by different sustainability's criteria. To address this gap, this research proposes a structural equation model, with six hypotheses, to quantitatively measure the effects of Lean Manufacturing and Industry 4.0, in Sustainability. To statistically validate such hypotheses, we collected 252 valid questionnaires from industrial companies of Iberian Peninsula (Portugal and Spain). Results show that: (1) it is not conclusive that Lean Manufacturing is correlated with any of the sustainability pillars; and (2) Industry 4.0 shows a strong correlation with the three sustainability pillars. These results can contribute as an important decision support for the industrial companies and its stakeholders, even because not all the results are in line with other opinions and studies.

Keywords: Lean Manufacturing; Industry 4.0; sustainability; economic; environmental; and social; structure equations modeling

1. Introduction

At present, Lean Manufacturing (LM), Industry 4.0 (I4.0), and Sustainability are important concerns for companies and in a general way for the society. The influence of the two production philosophies, LM and I4.0, in the three main pillars of sustainability—economic, environmental, and social—for industrial companies situated in Iberian Peninsula (Portugal and Spain) is the main objective of this work. More precisely, [The principal reasons and motivations to develop this study are related with: (1) There is no existing study using the structural equations modeling technique for both production philosophies (LM and I4.0) and the pillars of sustainability; (2) because the knowledge of these potential correlations can influence important decisions for the industrial companies and its stakeholders. In fact, the topic of this work concerns all parts of society minimally affected by the outcomes of LM and, more recently, with I4.0. In relation to this, the uncertainty is large, and few concerns are now appearing from different sides of the society, e.g., related with the future of the employment.

Lean manufacturing (LM), or lean production, in time philosophy, Toyota production system, or more often just "Lean", is a philosophy which considers the utilization of resources for any goal with value creation for the end consumer. It targets the elimination of wasteful activities involved in the value system [1,2]. LM is supported by a set of well-known tools to operationalize its goals, either at a strategic level or at an operational level, and the basis of the philosophy considers the human being as an import issue in all its decisions. Unfortunately, nowadays the companies that introduce LM practices tend to forget this human aspect, and principally focuses on waste reduction, a side that has brought well known results for the production systems.

The Industry 4.0 or I4.0 for short [3–6], is starting to revolutionize communities requiring a significant upgrade not just in terms of technology. With the advent of exponential technology and high speed and big data processing capabilities, high levels of digitalization regarding all kind of processes in companies are also required. These processes have to become supported by appropriate infrastructures, such as: IoT, IIoT, RFID, CFS, and Cloud, [3–10] along with additional fitting hardware and software means for enabling a full vertical and horizontal integration of all companies' functions, from the administrative level down to the shop floor. Additive manufacturing [9] and collaborative robots [11], for instance, are expected to play a crucial role in this direction, but also suitable organizational structures and business models, and along with appropriate production and decision methods and supporting tools are going to be necessary to enable a successful ingress on I4.0. Moreover, according to [6,12] the principles of Industry 4.0 are the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customized production. Such data plays a crucial role for enabling different kinds of decision making, for instance regarding the prioritization of production orders, and tasks optimization, along with other needs, such as maintenance related to each one's requirements [13].

The concept of sustainability has received increasing global attention from the public, academic, and business sectors. The World Commission on Environment Development (WCED) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [14]. Putnik and Ávila in their special issue of governance and sustainability [15] reinforce the importance of the theme and even give the character of ubiquity in the word 'sustainability'. Nidumolu et al., in 2009 [16] explains why sustainability is now the key driver of innovation according with their study of sustainability initiatives of 30 large corporations. Almeida et al., in 2016 [17] says even that it is common to ignore the interdependence of the sustainability pillars for short periods of time, but history has shown that before long, mankind is reminded of it through some types of alarms or crisis.

In spite of everyone knowing the 3 pillars of sustainability (economic, environmental, and social), it is quite difficult to choose the criteria/KPI to characterize and evaluate the degree of sustainability of each organization. Because our work intends to analyze the relation between LM and sustainability, and I4.0 and sustainability, the criteria that characterize the three pillars of sustainability are crucial to develop the current research. Through a literature search related with the theme were found several works covering different kinds of applications areas, such as agriculture, civil engineering, manufacturing, energy production, and mining. However, only few are framed with manufacturing applications, which is the principal area of our study. To refer those more relevant to our work, the study of a set of researchers [18–24] was the basis to define the criteria for the pillars of sustainability. In fact, there is no existing universal model to assess the level of sustainability for a manufacturing system, and the models are different. For that reason and considering the combination/integration of both methodologies to define criteria for sustainability assessment, strongly recommended by Waas et al., in 2014 [25]: the "top-down"/"expert-driven" and "bottom-up"/"stakeholder-driven", because a combination of the different kinds of knowledge, from the citizen to the experts, defined the criteria to assess the sustainability as used in the Table 1 Table 2 Table 3 Table 4 Table 5 Table 6.

To achieve the goal of this work, the rest of this paper is organized as follow. Section 2 identifies the main contributions of scientific and technical works in the relations between LM and Sustainability, and, I4.0 and Sustainability. Section 3 presents the general model used to study the problem and then is made the evaluation of the model and the results discussion in the Sections 4 and 5 respectively. To finalize, some conclusions and future works are made in Section 6.

2. Literature Review

The literature review presented in this section aims at serving as a basis for supporting the main purpose of this work, that will consider two main issues: (1) to accurately regard the theme of this work; (2) the knowledge needed to specify the main constructs of our proposed Structural Equation Modeling (SEM), further described in Section 4.

Regarding issue (1), the purpose is to identify if there are similar concerns among researchers' proposals, and if their works overlap our research proposal.

Assuming that issue 1 is accomplished, as it will be further exposed in this paper, the issue (2) is carried out through the identification of the main relations between LM and Sustainability, and I4.0 and Sustainability. In order to proceed with such identification are considered different kind of studies, including different statements of the researchers reviewed regarding this subject. This statements analyzed acted as a basic knowledge for the definition of the constructs of our proposed model. Therefore, we constructed focused tables to resume the main relations for further analysis through the constructs underlying our proposed model.

2.1. Lean Manufacturing and Sustainability

This sections discusses the relations between lean manufacturing (LM) and the 3 dimension of sustainability is the scope of this section. Several organizations have successfully achieved better results and higher competitiveness through LM implementation; however, others have not, as they were unable to sustain medium- and long-term results [26]. Companies that have adopted LM to improve their results also want to be seen as socially responsible. Sustainability is considered the new LM frontier [27]. Productivity and cost-saving are necessary for the economic survival of organizations. However, these tasks should be achieved in a sustainable way, by mitigating negative environmental and social impacts and contributing to a sustainable society [28].

Therefore, in the following Tables 1–3, some main recent contributions, arising from a set of researchers in this cross LM—Sustainability area, and underlying main influences considered are summarized.

2.1.1. Influence of Lean Manufacturing in Economic Dimension

Examples of initiatives leading to cost savings and process performance are many attending the influence of LM in the economic dimension. However, for the rest of the criteria considered, the references are scarce and even for the turnover influence were not found references.

In Table 1, a resume about some main contributions regarding the relation or influence of LM in the economic dimension of sustainability are presented.

Table 1. Influence of Lean Manufacturing in economic dimension.

Dimension	Influence	References
Economic	Increase profits	Pampanelli et al. (2014) [28]
	Increase turnover	Not identified
	Increase market share of the products	Wilson (2010) [29]
	Decrease operational costs	Zhu, et al., 2008 [30]; Mollenkopf et al., 2010 [31]; Sezen et al., 2011 [32]; Lozano and Huishingh, 2011 [33]; Azevedo et al., 2012 [34]; Díaz-Reza, et al., 2016 [35]; Gupta, et al., 2018 [36];
	Increase process performance	Shah and Ward, 2007 [37]; Sezen, et al., 2011 [38]; Ng, et al., 2015; Díaz-Reza, et al., 2016 [35].

2.1.2. Influence of Lean Manufacturing in Environmental Dimension

According to Jabbour et al. [38–40] support for environmental management tends to be greater when companies adopt LM practices, which would improve their environmental performance. Also Ng et al., in 2015 [41] refer that LM reduce environmental impact and increase environmental benefits. According to Yang et al., in 2011 [42], that explored the relationship between LM practices, environmental management, and business performance, the results of their research propose that lean manufacturing experiences are positively related to environmental management practices. In spite of that some authors refer the good influences of LM in Sustainability, for the influence of production of renewal energy and for the influence in collaboration with partners that follow good environmental practices were not found references.

In Table 2, a resume about some main contributions regarding the relation or influence of LM in the environmental dimension of sustainability are presented.

Table 2. Influence of Lean Manufacturing in the environmental dimension.

Sustainability Dimension	Influence	References
Environmental	Decrease industrial waste	Souza and Alves, 2017 [26]; Wilson, 2010 [29]; Torielli, et al., 2011 [43]; Vinodh, et al., 2011 [44]; Gupta, et al., 2018 [36]; Azevedo, et al., 2012 [34]; Hajmohammad, et al., 2013 [45].
	Decrease energy consumption of non-renewal energy sources	Ioppolo, et al., 2014 [46].
	Increase the production of renewal energy	Not identified
	Increase the practice of circular economy	Nunes and Bennett, 2010 [47]; Zhao and Chen, 2011 [48]; Ming and Xiang, 2011 [49]; Ashish, et al., 2011 [50]; Liao, et al., 2013 [51].
	Increase the collaboration with partners that follow good environmental practices	Not identified

2.1.3. Influence of Lean Manufacturing in Social Dimension

The influence of LM is one of the major concern of our study and in the beginning of its implementation inside the Toyota production system. Between the seven major gaps identified by Cherrafi et al., in 2016 [52] in the conclusions of their research, two of them are clearly framed with the goal of our study: the need to study the human side in a more comprehensive manner, and the need to develop an integrated metrics and measurement system to measure the relation between lean and sustainability performance. Gupta et al. [36], in their work related to environmental sustainability, refer also to how future studies could bring the social dimension. In spite of some concerns related to the social pillar, most of the influences did not find any reference that reflects with certainly the low importance that has been given to the topic of sustainability.

In Table 3, some main contributions regarding the relation or influence of LM in the social dimension of sustainability are presented.

Table 3. Influence of Lean Manufacturing in social dimension.

Dimension	Influence	References
Social	Increase the number of employees	Not identified
	Increase the salary remuneration	Not identified
	Increase the quality of work conditions	Ng, et al., 2015 [41]; Taubitz, 2010 [53]; Lozano and Huishingh, 2011 [33]; Vinodh, et al., 2011 [44]; Ioppolo, et al., 2014 [46];
	Increase the conditions of the surrounding society	Not identified
	Decrease working accidents	James, et al., 2013 [54];
	Increase the participation of its employees in decision-making	Taubitz, 2010 [53]; Vinodh, et al., 2011 [44]; Jabbour, et al., 2012 [39].
	Increase the number of employees with some degree of disability.	Not identified
	Increase the contract duration of its collaborators	Not identified

2.2. Industry 4.0 and Sustainability

In this upcoming era of the I4.0 as many changes are expected to occur in the everyday life of people and companies [40], one important and big question we now have to face, among several others, is: "Can industry 4.0 revolutionize the environmentally-sustainable manufacturing wave? In order to make a contribution in this direction, in this work we intend to further explore several contributions and opinions arising from different authors and sources to try to analyze some main positive and negative impacts that I4.0 may have in terms of the three main dimensions of the sustainability concept—economic, social, and environmental—in the context of Industrial companies.

Therefore, in the following Tables 4–6, some main recent contributions, arising from a set of researchers in this cross I4.0— the sustainability area and underlying main dimensions considered are summarized.

2.2.1. Influence of I4.0 in Economic Dimension of Sustainability

It is expected that I4.0 will drive companies, for instance industrial ones, to more favorable economic situations, though massive savings to be reached by reducing operators or man power, by saving energy, and by doing work effectively and efficiently, and by reducing production time and improving productivity, among other beneficial situations [11,40,55,56].

In Table 4, a resume about some main contributions regarding the relation or influence of I4.0 in the economic dimension of sustainability are presented.

Table 4. Influence of Industry 4.0 (I4.0) in economic dimension.

Dimension	Influence	References
Economic	Increase: profits, value creation, efficiency, flexibility, and competitiveness	Müller, et al., 2018 [56]; Nagy, et al., 2018 [57]; Laudien, et al., 2017 [58]; Rennung, et al., 2016 [59]; Erol, et al., 2016 [5]; Rehage, et al., 2013 [60]; Rudtsch, et al., 2014 [61]; Brettel, Klein, and Friederichsen, 2016 [62]; Stock and Seliger, 2016 [63];
	Increase turnover, and create new business models	Arnold, et al., 2015 [64]; Brettel, et al., 2014 [62]; Burmeister, et al., 2016 [65]; Hofmann and Rüsch, 2017 [66]; Duarte and Cruz-Machado, 2017 [67]; Bechtsis, et al., 2017 [68]; de Sousa Jabbour, et al., 2018 [40]; Gilchrist, 2016 [7]; Branke, et al., 2016 [66]; Schmidt, et al., 2015 [67]; Schmidt, et al., Branke, et al., 2016 [69]; 2015 [70]; Nagy, et al., 2018 [57]; Glas, et al., 2016 [71];

Table 4. *Cont.*

Dimension	Influence	References
	Improve: market share of the products, supply chains, and its management performance and security	Dubey, et al., 2017 [72]; Branke, et al., 2016 [69]; Hofmann and Rüsch, 2017 [66]; Stock and Seliger, 2016 [63]; Tjahjono, et al., 2017 [73]; Sommer, 2015 [74]; Wang, et al., 2015 [20]; Lee, Kao, and Yang, 2014 [13]; Luthra and Mangla, 2018 [75]; Nagy, et al., 2018 [57];
	Decrease operational costs	Shrouf, et al., 204 [4]; Waibel, et al., 2017 [76]; Yang, 2014 [13]; Schmidt, et al., 2015 [70]; Stock and Seliger, 2016 [63];
	Improve processes performance, increase renewable resources, and improve circular economy	Jabbour, et al., 2017 [40]; Oettmeier and Hofmann, 2017 [77].

2.2.2. Influence of I4.0 in Environmental Dimension of Sustainability

In terms of environmental impact, I4.0 may have either positive or negative impacts, depending on several different kinds of analysis that may be carried out, across small to big enterprises [40,66,78].

In Table 5, a resume about some main contributions regarding the relation or influence of I4.0 in the environmental dimension of sustainability are presented.

Table 5. Influence of I4.0 in environmental dimension.

Sustainability Dimension	Influence	References
Environmental	Decrease industrial waste	Shrouf, et al., 2014 [4]; Waibel, et al., 2017 [76]; Yang, 2014 [13]; Oettmeier and Hofmann, 2017 [77]; Stock and Seliger, 2016 [63]; Wang, et al., 2015 [20];
	Decrease energy consumption of non-renewal energy sources	Hofmann and Rusch, 2017 [66]; Fritzsche, et al., 2018 [79];
	Increase production of renewal energy	Lund, and Mathiesen, 2019 [80];
	Increase practice of circular economy	Jabbour, et al. (2017) [40]; Branke, et al., 2016 [66];
	Increase collaboration with partners that follow good environmental practices	Zawadzki and Żywicki, 2016 [78]; Hofmann and Rüsch, 2017 [66];
	Decrease resources consumption, global warming, climate changes, and energy requirements	Tseng, et al., 2018 [81]; Fritzsche, et al., 2018 [79].

2.2.3. Influence of I4.0 in Social Dimension of Sustainability

People in general and operators in particular seem to become increasingly worried about the upcoming increasing era of I4.0 due to many reasons, mainly in regard of work opportunities [57]. Although, some more optimistic ones are even trying to foresee very beneficial conditions and opportunities to workers and people in general [55,62,69,82,83].

In Table 6, a resume about some main contributions regarding the relation or influence of I4.0 in the social dimension of sustainability are presented.

Table 6. Influence of I4.0 in social dimension.

Dimension	Influence	References
Social	Increase number of employees	Branke, et al., 2016 [69]; Brettel, Klein, and Friederichsen, 2016 [62];
	Improve working conditions (e.g., for employees with some disability, training courses, salary, among others)	Shamim, et al., 2016 [82]; Hirsch-Kreinsen, 2014 [83]; Kiel, et al., 2017 [55];
	Improve conditions of the surrounding society	Branke, et al., 2016 [66]; Shamim, et al., 2016 [82];
	Decrease working accidents	Brettel, Klein, and Friederichsen, 2016 [62];
	Increase participation of employees in decision-making	Branke, et al., 2016 [69]; Brettel, Klein, and Friederichsen, 2016 [62].
	Increase contract duration of employee and collaboration among stakeholders	Yang, 2014 [13]; Duarte and Cruz-Machado, 2017 [67]; Pfohl, et al., 2017 [84]; Shamim, et al., 2016 [82].

2.3. Main Remarks from State-of-the-Art Research

We proposed to postpone the analysis regarding the tables presented for this subsection, because to develop our model it is necessary to have a global analysis over the main contributions arising from state-of-the-art research. Therefore, the main remarks that should be pointed out are the following:

- The first remark is that none of the researchers in their works did cover all the considered main influence criteria exposed in Tables 1–6;
- The second remark is that none of the works analyzed treats this subject through SEM;
- The third remark is that some criteria's influence are more considered than others, namely, for few of them were not found any reference.

Furthermore, we can realize that the two main issues presented at the beginning of this section were accomplished through the summarized review presented on the Tables 1–6. In short, this work focuses a different approach than that the literature, and puts forward the main constructs to be used in our proposed model, as described in the next section.

3. Research Model

This section presents the global framework of our model and the methodology used in this work.

3.1. General Model

In this work, to evaluate the relationship between LM and Sustainability, and, I4.0 [85–87] and sustainability—the problem of our study—were defined two main sets of hypotheses. The first set of hypotheses is related to LM and Sustainability (H1, H2, and H3), and the second one is related to I4.0 and sustainability (H4, H5, and H6), which are related to the economical (EcS), environmental (EnS), and social (SoS) pillars, as shown below.

Hypothesis 1 (H1). *The industrial companies' perception on Economic Sustainability is positively related to Lean Manufacturing.*

Hypothesis 2 (H2). *The industrial companies' perception on Environmental Sustainability is positively related to Lean Manufacturing.*

Hypothesis 3 (H3). *The industrial companies' perception on Social Sustainability is positively related to Lean Manufacturing.*

Hypothesis 4 (H4). *The industrial companies' perception on Economic Sustainability is positively related to Industry 4.0.*

Hypothesis 5 (H5). *The industrial companies' perception on Environmental Sustainability is positively related to Industry 4.0.*

Hypothesis 6 (H6). *The industrial companies' perception on Social Sustainability is positively related to Industry 4.0.*

By the present model, it is defined that LM and I4.0 are independent variables (exogenous constructs), therefore, these variables do not have an arrow pointing to it from another construct, and EcS, EnS, and SoS are variables dependents (endogenous variables), therefore, the mentioned constructs have a least one arrow pointing to it from another construct. As can be seen, the five constructs (two exogenous and three endogenous) and the six working hypotheses are graphically represented in Figure 1 that represents our initial general model.

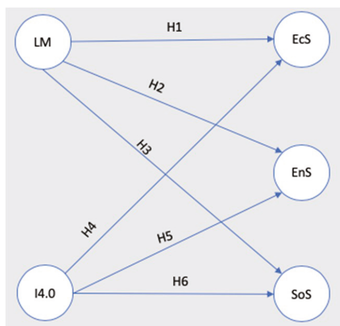


Figure 1. Initial general model.

In order the need to represent theoretical models that allow the identification of causal and/or hypothetical relationships between variables, and to validate the theoretical premise that the present work intends to prove, namely, the relation between the manufacturing concepts Lean Manufacturing and Industry 4.0 with Sustainability (Economic, Environment, and Social), we established the use of the modeling technique called Structural Equation Modeling (SEM) [88,89]. This methodology is identified as multivariate analysis, usually expressed in linear models that include measurement errors associated with the established variables in the model [89–91].

In this work, the analysis is divided into two parts the Confirmatory Factor Analysis (AFC) for the measurement model and the structural model analysis. So, based in the SEM method, it is established by two models [86,88]: Measurement Model and Structural Model. The Measurement Model (MM) establishes the relationships between the constructs and its manifested variables, in which the construct is formed by manifested variables through the accomplishment of the Confirmatory Factor Analysis (AFC) that calculates and specifies how the constructs are measured from the manifested variables. In the Structural Model (SM) the relationship between exogenous and endogenous constructs is defined. In this model is established the influence (direct or indirect) that the exogenous constructs apply on the endogenous constructs. In the development of the present work, it was used the software IBM SPSS Amos, version 24, from IBM Corp., 2016 [89] to employ the SEM method.

3.2. Survey and Data Collection

In this study a set of variables were established (see Table 7) based on the literature review carried out and summarized in Section 2, and our main findings for the considered problem.

Table 7. Constructs and manifested variables.

Constructs	Manifested Variables
Exogenous	
Lean Manufacturing ($\xi1$)	Pull production (X1) Product defects (X2) Failures (X3)
Industry 4.0 ($\xi2$)	Big data (X4) Autonomous robots (X5) Digitalization (X6)
Endogenous	
Economic Sustainability ($\eta1$)	Profits (Y1) Turnover (Y2) Market share (Y3)
Environmental Sustainability ($\eta2$)	Energy consumption (Y4) Circular economy (Y5) Environmental practices with partners (Y6)
Social Sustainability ($\eta3$)	Salary remuneration (Y7) Work conditions (Y8) Surrounding society (Y9)

Next, a survey based on these premises was developed, validated by three experts, and put available to a widened industrial community of the Iberian Peninsula. The survey was applied only in industrial companies located in Portugal and Spain, and it was collected 252 validated answers in a total of 306 answers obtained. During the survey, the respondent answered in a 5-points Likert scale in which 1 means the respondent completely disagree with the statement (lowest value) and 5 that the respondent completely agree with it (higher value).

The sample size establishes the error estimation of the sample. Since this is a critical aspect to be considered, it must be established a minimum sample size [90]. In this work the minimum sample size was defined as referred by Westland, in 2010 [91], and the value obtained was 200. Therefore, our sample of 252 validated answers did fulfill the imposed requirement.

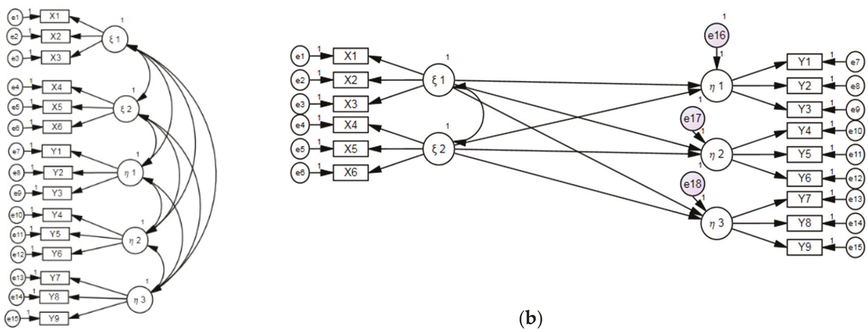
4. Evaluation Models

In this section will be presented both measurement model (MM) and structural model (SM) used, as represented through Figure 2, which are composed by five constructs (Lean, Industry 4.0, Economic Sustainability, Environmental Sustainability, and Social Sustainability), each one measured by three indicators, totalizing 15 indicators, all measured in Likert scales (1–5). The factorial weights of each manifest variable (λ), of each coefficient estimation (β) and of each error (e) are obtained through the Maximum Likelihood Method [86–88].

It is mandatory to analyze the fit and validity of the identified variables, to assess the quality of the collected data, for further evaluation of the defined general model. Moreover, as a consequence perform the evaluation of the present work. The SEM method uses several different validation indexes, and in this study, it is considered the most common absolute, relative, parsimony-adjusted, population discrepancy and information theory-based indexes, whose specific reference is presented ahead of each corresponding index are summarized below.

- Absolute indices: these indices compare a specific model of adjustment with its saturated model.
  - $\chi2/df$ ratio (chi-square and degrees of freedom ratio) [92,93];
  - Goodness of Fit Index (GFI) [92,93];

- Relative indices: relative adjustment indices compare the specific adjustment model to the worst possible adjustment (without relations between the manifested variables) and to the best possible adjustment (saturated model).
    - Comparative Fit Index (CFI) [92,93];
    - Tucker Lewis Index (TLI) [92];
    - Incremental Fit Index (IFI) [93,94];
- Parsimony-adjusted indices: penalize the relative indices by complexity and perform an improvement in the model so as to bring it closer to the saturated model, through the inclusion of free parameters.
    - Parsimony CFI (PCFI) [95];
    - Parsimony GFI (PGFI) [95];
- Population discrepancy index: this index reflects the adjustment of the model at the sampling moments (means and sample variances) with the population moments (means and population variances) by the comparison effect.
    - Root Mean Square Error of Approximation (RMSEA) [92];
- Information theory-based index: this index is pertinent to compare several alternative models with data adjustments.
    - Akaike Information Criterion (AIC) [96].



(**a**) (**b**)

Figure 2. (**a**) Measurement model (**b**) structural model.

All the referenced indices are summarized in the Table 8, and the corresponding adjustment measures to achieve the indices values for a good fit. Additionally, it is presented the macros used in the software IBM SPSS Amos.

Table 8. Adjustment indices and measures.

Adjustment Indices	Adjustment Measures	Macro in Amos SW	References
χ2/df	<3	\cmindf	(Hu and Bentler, 1999), (Wei et al., 2010) [92,93];
GFI	>0.9	\gfi	(Hu and Bentler, 1999), (Wei et al., 2010) [92,93];
CFI	>0.9	\cfi	(Hu and Bentler, 1999) [92]; (Wei et al., 2010), (Singh, 2009) [93,97];
TLI	>0.9	\tli	(Hu and Bentler, 1999), (Singh, 2009) [92,97];
IFI	>0.9	\ifi	(Santora and Bentley, 1990), (Wei et al., 2010) [93,94];
PCFI	>0.6	\pcfi	(Mulaik et al., 1989) [95];
PGFI	>0.6	\pgfi	(Mulaik et al., 1989) [95];
RMSEA	<0.08; $p > 0.05$	\rmsea \pclose	(Hu and Bentler, 1999), (Wei et al., 2010) [92,93];
AIC	Smaller than the independent model	\aic	(Schmitt, 2011) [96].

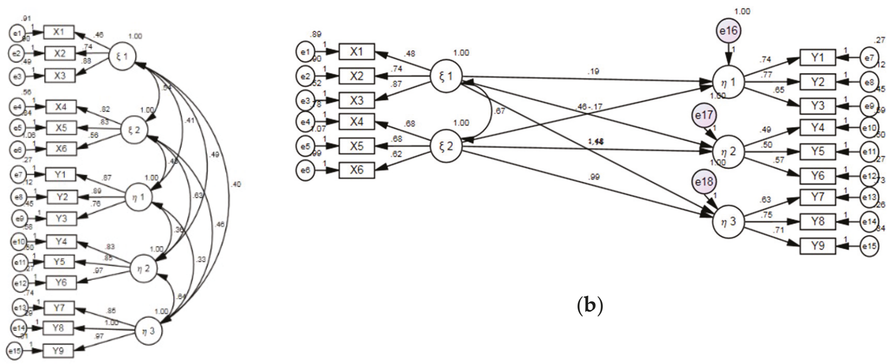
5. Results Discussion and Practical Implications

This section is divided into two subsections, the first one about the analysis of the mains results obtained, and the second one focused on the discussion on how these results may further support decision making in industrial companies and among their stakeholders. In the subsection about results discussion is first performed an estimation of the parameters of the models (MM and SM). Next, the parameters of the MM are analyzed and evaluated, and after an evaluation regarding the quality of the adjustment indices of the MM and the SM models is addressed.

5.1. Results Discussion

Regarding the estimates of the parameters of the models, using the SPSS Amos software, version 24 [89], with the Maximum Likelihood Method, the factorial and structural weights were obtained. In Figure 3a it is presented the relation between the constructs of MM, factorial weights, fit and errors. All constructs ($\xi1$, $\xi2$, $\eta1$, $\eta2$, $\eta3$) are based on the manifest variables ($\xi1$ = X1, X2, X3; $\xi2$ = X4, X5, X6; $\eta1$ = Y1, Y2, Y3; $\eta2$ = Y4, Y5, Y6; $\eta2$ = Y7, Y8, Y9) and, in this model, the constructs have a relation from all to all in order to provide the measurement evaluation in the MM. Figure 3b presents the SM, factorial weights, fit, and errors. For this model, the relations of the constructs are based on the initial general model (Figure 1), establishing the SM. Additionally, it was created a correlation between constructs LM ($\xi1$) and I4.0 ($\xi2$), because it seems an important issue, to be studied also.

Concerning the analysis and evaluation of the parameters of the MM, the results for LM ($\xi1$) show good fit and validity of the indicators, due to the factorial weights being higher than 0.25 [92]. The most convergent indicators are the Failures (X3) with a factorial weight of 0.88, followed by product defects (X2) with a factorial weight of 0.74 and, finally, the pull production (X1) with a weight of 0.46. Good fit and validity have also been demonstrated in the indicators of the I4.0 construct ($\xi2$), presented in decreasing order, Autonomous robots (X5), Big data (X4), and Digitalization (X6), with the factorial weight of 0.83, 0.82, and 0.56, respectively. Based on this data, it is possible to realize that the manifest variables that did show a higher influence for each of the defined exogenous constructs are: Failures (X3) for the LM construct ($\xi1$), and Autonomous robots (X5) for the I4.0 construct ($\xi2$).



(**a**) (**b**)

Figure 3. (**a**) Relation between the constructs of Measurement Model (MM), (**b**) Structural Model (SM), factorial weights, and fit.

The indicators Turnover (Y2), with a factorial weight of 0.89, Profits (Y1), with a factorial weight of 0.87, and Market share (Y3), with a factorial weight of 0.76, for Economic Sustainability (η1). In the Environmental Sustainability (η2) the higher indicator is Environmental practices with partners (Y6), with a factorial weight of 0.97, followed by Circular economy (Y5), with a factorial weight of 0.85, and Energy consumption (Y4), with a factorial weight of 0.83. Moreover, for Social Sustainability (η3), the indicators Work conditions (Y8), with a factorial weight of 1.00, Surrounding society (Y9), with a factorial weight of 0.97, and Salary remuneration (Y7), with a factorial weight of 0.85, also suggest a good fit and validity of the indicators of the endogenous constructs. Based on this data, it is possible to realize that the manifest variables that did show a higher influence for each of the defined endogenous constructs are: Turnover (Y2) for the Economic Sustainability (η1), Environmental practices with partners (Y6) for the Environmental Sustainability (η2), and Work conditions (Y8) for the Social Sustainability (η3).

The evaluation of the MM was performed, then the quality of the adjustment indices was obtained and the values are presented in Table 9.

Table 9. Adjustment validation of the MM. GFI: Goodness of Fit Index; CFI: Comparative Fit Index; TLI: Tucker Lewis Index; IFI: Incremental Fit Index; PCFI: Parsimony CFI; PGFI: Parsimony GFI; RMSEA: Root Mean Square Error of Approximation; AIC: Akaike Information Criterion.

Adjustment Measures	Adjustment Obtained Value	Adjustment Criterion
χ^2/df	2.015	<3
GFI	0.923	>0.9
CFI	0.951	>0.9
TLI	0.936	>0.9
IFI	0.952	>0.9
PCFI	0.724	>0.6
PGFI	0.615	>0.6
RMSEA	0.064 (p = 0.058)	<0.08; p > 0.05
AIC	241.163 < 1787.589	Smaller than the independent model

Due to the obtained value on the indexes, it is confirmed that all index values are within the defined criteria. After the evaluation of the MM, the SM was evaluated and, based on the defined quality of the adjustment indices, the values obtained are mentioned in Table 10.

Table 10. Adjustment validation of the SM.

Adjustment Measures	Adjustment Obtained Value	Adjustment Criterion
χ^2/df	2.273	<3
GFI	0.908	>0.9
CFI	0.936	>0.9
TLI	0.919	>0.9
IFI	0.937	>0.9
PCFI	0.740	>0.6
PGFI	0.628	>0.6
RMSEA	0.071 (p = 0.006)	<0.08; p > 0.05
AIC	262.657 < 1787.589	Smaller than the independent model

Based on the values shown in Table 9; Table 10 an analysis of the results of the validation of the theoretical models developed can be reached. When applying the Confirmatory Factor Analysis in the Measurement Model (MM), the values of the adjustment quality (χ^2/df = 2.015, GFI = 0.923, CFI = 0.951, TLI = 0.936, IFI = 0,952, PCFI = 0.724, PGFI = 0.615, RMSEA = 0.064, and AIC = 241.163) confer a reliability and validity with a good fit. In the evaluation of the quality of the Structural Models (MEs), the results obtained (χ^2/df = 2.273, GFI = 0.908, CFI = 0.936, TLI = 0.919, IFI = 0.937, PCFI = 0.740, PGFI = 0.628, and RMSEA = 0.071, AIC = 262.657), suggest that a good adjustment was reached.

Once again, all obtained index values are within the established range of the adjustment measures. Regarding the estimates for the parameters of the estimation of the structural relationships in the SM, the results shown in Table 11 were obtained.

Table 11. Estimates of the SM and synthetized frame of the hypothesis.

Hypothesis	Exogenous Construct	Endogenous Construct	Est.	SE	CR	p-Value	Conclusion
H1.	Lean	Economic Sustainability	0.187	0.133	1.405	0.16	Not confirmed
H2.	Lean	Environmental Sustainability	−0.167	0.365	−0.457	0.648	Not confirmed
H3.	Lean	Social Sustainability	−0.142	0.280	−0.508	0.611	Not confirmed
H4.	Industry 4.0	Economic Sustainability	0.457	0.132	3.466	<0.001	Confirmed
H5.	Industry 4.0	Environmental Sustainability	1.482	0.477	3.108	0.002	Confirmed
H6.	Industry 4.0	Social Sustainability	0.994	0.297	3.341	<0.001	Confirmed

Concerning the analysis of the results of the assumptions of the SM, presented in Table 11, through the relationships established between the constructs are evaluated, and the hypotheses of the model are tested, as it is the main concern of this work. In the SM the hypotheses H4, H5, and H6 were confirmed, while the hypotheses H1, H2, and H3 were not confirmed (H1: p = 0.16 > 0.05, H2: p = 0.648 > 0.05, H3: p = 0.611 > 0.05). Additionally, a correlation (0.68) between Lean Manufacturing and Industry 4.0 is also confirmed in SM.

The results of our study, based on the developed model, and obtained through the Maximum Likelihood Method, show that: (1) it exists a strong relation between I4.0 and the three pillars of Sustainability, with a strongest factorial weight for Environmental Sustainability (1.482), followed by Social Sustainability (0.994), and the lowest for Economic Sustainability (0.457); (2) it is not confirmed that exists a relation between LM and Sustainability; (3) cumulatively, it was found out that exists a correlation between LM and I4.0.

5.2. Practical Implications

The results of this study are not totally aligned with the initial expectations regarding the relation between LM and Sustainability stressed by several authors, for instance the authors reviewed in Section 2.1. Although, it does not mean that no relation at all does exist. However, this study does not confirm that relation. This is possibly explained due to the fact that LM focuses its attention on a current state of a company, without a concern regarding a global, integrative and transformative vision of companies, and subject to dynamic and turbulent environments, which is a general characteristic of them, namely industrial ones. This is due to the fact that LM is based on a "linear", non-holistic thinking, thus not taking into account the need to include other more sustainable paradigms. In terms of practical implications for the companies, now they have a structured study to be considered when faced with a decision making process to implement LM. From this moment, the fact is that the companies know that it is not confirmed that LM is related to Sustainability.

The other part of the results, regarding the relation between I4.0 and Sustainability, was confirmed to be aligned with most of the researchers' contributions in topics of this field, for instance, the authors reviewed in Section 2.2. However, it does not mean there do not exist further concerns about I4.0 implications in the three pillars of Sustainability, namely in the social one, principally for the employees. In terms of practical implications for the companies and their stakeholders, this study assures the existence of relation between I4.0 and Sustainability. This can mean that companies have now a stronger knowledge to further decide about I4.0 implementation and its implications in sustainability.

6. Conclusions

In this paper, after an introduction to the principal goals of the work and the explanation of the meaning of the three main elements underlying this work (LM, I4.0, and Sustainability), was done a literature review mainly focused in the influence of LM in Sustainability and of I4.0 in Sustainability.

Based on that revision, and as far as our knowledge, were obtained the following three main remarks: (1) none of the researchers in their works did cover all the considered main influence criteria exposed; (2) none of the works analyzed treats this subject through SEM; and (3) some criteria' influence are more considered than others, for instance, for few of them were not found any reference. Then, it was validated that this work focuses a different approach than the literature analyzed, and it was possible to put forward the main constructs and the manifested variables used in our proposed model. To address that gap, it was proposed a structural equation model, based on two exogenous constructs (LM and I4.0) and three endogenous constructs (EcS, EnS, and SoS), each construct composed by three manifest variables, and with six hypotheses, to quantitatively measure the effects of LM and I4.0, in Sustainability. Moreover, in order to statistically validate such hypotheses, a set of 252 valid questionnaires from industrial companies of Iberian Peninsula (Portugal and Spain) were analyzed.

The validation of the MM was obtained through the application of the Confirmatory Factor Analysis and the corresponding values of the adjustment quality conferred a reliability and validity with a good fit. Concerning the assumptions of the SM values analysis, the relationships established between the constructs were evaluated and the hypotheses of the model tested, as it was a main concern of this work. Then, the hypotheses H4, H5, and H6 were confirmed, while the hypotheses H1, H2, and H3 were not. Additionally, a correlation between LM and I4.0 was also confirmed.

As a global conclusion, the results obtained through the study carried out enable to state that exists a relation between I4.0 and Sustainability, and a not confirmed relation between LM and Sustainability. These conclusions can contribute as an important decision support for the industrial companies and its stakeholders, even because not all the results are in line with other opinions and studies. Moreover, this can mean that companies have now a stronger knowledge to further decide about the implementation of LM and I4.0, and its implications in Sustainability.

The results of this study are limited by the region object, in this case the Iberian Peninsula, and for industrial companies. For that reason, further studies should consider other countries. Also, because social sustainability is an important concern for the future of society, namely, concerning the influence of I4.0, more variables will be considered in the presented model to evaluate more deeply its influence in the ambit of social sustainability.

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Optimal Joint Production and Emissions Reduction Strategies Considering Consumers' Environmental Preferences: A Manufacturer's Perspective

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Abstract: Carbon cap-and-trade mechanism is a government-mandated, market-based scheme to reduce emissions, which has a significant effect on manufacturers' operation decisions. Based on the cap-and-trade mechanism, this paper studies the joint production and emission reduction problem of a manufacturer. The manufacturer faces emissions-sensitive demand impacted by consumers' environmental preferences (CEP). An extended newsvendor model is used to find the optimal production quantity and emissions reduction quantity. We explore the impacts of market price of carbon credits, emission reduction investment coefficient and CEP on the optimal strategies. Numerical examples are provided to illustrate the theoretical results and orthogonal experimental design technique was applied to find robust system parameters. It is concluded that among all parameters, emissions cap has the greater impact on the expected profit, which is followed by than the market price of carbon credits. This means that the government plays a major role in economic development. The total carbon emissions are mainly affected by the carbon trading price and the product's sale price, which indicates the carbon trading market and product market play a larger role in controlling environmental benefits. Several valuable managerial insights on helping governments and industries understand how market conditions change and make better long-term decisions are further concluded.

Keywords: cap-and-trade; production; carbon emissions reduction; consumers' environmental preferences; newsvendor model

1. Introduction

Worldwide industrial activities account for about one third of total greenhouse gasses (GHGs) emissions. Greenhouse gasses such as carbon dioxide, nitrous oxide and methane are the leading cause of global warming and climate change [1]. With the rapid growth of industry, there is a critical need to reduce GHGs emitted by manufacturers. Among all the GHGs, carbon dioxide accounts for 65% of the total emissions [2]. Since the implementation of the Kyoto Protocol in 1997 and the Paris Climate Agreement in 2015, China, Korea and several European countries have enacted a variety of carbon policies and legislation to reduce carbon emissions [3]. For example, in 2005, Europe established the European Union Emissions Trading Scheme (EU ETS), which is the world's most profound carbon trading mechanism. Based on carbon trading mechanisms, governments control carbon emissions by allocating free carbon quotas (called emissions cap) to enterprises [4]. If a manufacturer emits more carbon than the emissions cap, it has to buy quotas to emit extra carbon; if a manufacturer emits less carbon than the emissions cap, it can sell surplus carbon credits to gain extra revenue [5]. In China, seven carbon trading centers placed in Beijing, Shanghai, Guangdong and four other cities have implemented a carbon emissions trading mechanism [6]. By December 2017, these trading centers have completed 0.47 billion tons of carbon credits transaction in total and the turnover was more than 0.014 billion USD. It shows that the carbon trading mechanism could affect manufacturers' profits [3,7,8].

In recent decades, people have become more concerned about environmental issues and been willing to buy low-carbon products [9,10]. The AliResearch Institution, which is a non-profit agency in China, estimated that the total number of consumers that prefer low-carbon products increased by 14 times in the past four years and reached 65 million in 2015 [11]. Thus, affected by the consumers' environmental preferences (CEP), many manufacturers such as P&G and HP have motivations to invest in low-carbon technologies to reduce carbon emissions [12]. Then CEP may affect manufacturer's profit and total carbon missions. As decision makers, under the cap-an-trade mechanism, all manufacturers need to re-determine their operational decisions, that is, the optimal production quantity and the emissions reduction per unit of product, to maximize their profits.

Based on the scenario mentioned above, we want to answer the following questions:

1. How does the manufacturer who sells a seasonal product with random demand determine the optimal production and carbon emissions reduction per unit of product with CEP under cap-and-trade mechanism?
2. What effects do the demand parameters, cost parameters and carbon emissions parameters exert on the optimal strategies, total carbon emissions and expected profit of the manufacturer?
3. What management insights should be given to manufacturers?

To solve the first question, the classical newsvendor framework is extended by dividing the uncertainty demand into three parts: the price-related demand, the carbon emissions reduction-related demand and the random perturbation term. To maximize a manufacturer's profits, this model is applied to derive the optimal production quantity and emissions reduction per unit of product considering the cap-and-trade mechanism and CEP. Numerical examples are provided to develop the robustness of demand, costs and regulation parameters via the orthogonal experimental design technique and investigate the impacts of these parameters on a manufacturer's profit and total carbon emissions.

2. Literature Review

Motivated by such practical opportunities and challenges, environment protection has been emphasized in operations management. Considering CEP and the cap-and-trade mechanism, this paper focuses on finding the optimal production quality and carbon emissions reduction for a manufacturer who meets the uncertain demand. The literatures relating to this paper are shown as below.

2.1. Studies on the Operations Decisions Considering Carbon Emissions

Under carbon emissions regulations, the economic order quantity (EOQ) model was widely used to drive the optimal order quantity [13]. He et al. [14] the EOQ model to find the optimal lot-size and minimal emissions under cap-and-trade regulation. They investigated the impacts of production and regulation on the optimal. Bonney et al. utilized the extended EOQ model to study the carbon emissions and designed an inventory system [15]. Since the demand are constantly changing in the real world and, several scholars used stochastic models to derive optimal operational decisions for manufacturers. Chen and Monahan used a stochastic model to derive the optimal policies of production planning and inventory control policies under pollution control approaches in Reference [16]. Zhang et al. developed a dynamic model to analyze the optimal production strategy for a system with stochastic demand and emission permits in Reference [17]. Zhang and Xu proposed a multi-product production plan to meet stochastic demand under cap-and-trade mechanism [18]. The newsvendor model, which can be used to solve the order quantity optimization problem with stochastic demand, was applied in many studies. Song et al. investigated the classical single-period (newsvendor) problem under carbon emissions policies and found a manufacturer's optimal production quantity and corresponding expected profit [19]. Xu et al. analyzed a newsvendor problem with partial demand information under two kinds of carbon emission regulations, in which only the mean and variance of the demand distribution are known. In their research, two distributional robust models are formulated to determine the optimal order quantities [20]. Du et al. [21] took carbon footprint and CEP into account in the cap-and-trade system, they got the optimization production decision and found that firms could be motivated to reduce carbon emissions by CEP. Although they considered the behavioral factor of consumers who were willing to buy low-carbon products, they assumed that reverse demand function did not consider random factors. The models mentioned above assumed that the uncertain demand is solely affected by the sale price. They only derived optimal production/order quantities. However, incorporating market parameters such as demand and selling price into the model can provide an excellent vehicle for examining how operational problems interact with decision making [22]. In our study, manufacturers respond to CEP by introducing low carbon products to meet the demand. It is significant to jointly optimize the production and pricing.

2.2. Joint Pricing and Ordering Decisions in Extended Newsvendor Model

Some newsvendor models were extended to solve joint production and pricing problem. Whitin was the first to set selling price and stocking quantity simultaneously by using newsvendor model [23]. Mills, Karlin and Carr are early efforts that investigated the impacts of different demand processes on the seller's pricing and ordering decisions [24,25]. In their newsvendor models, the demand is generally divided into two parts, one is the price-related demand and the other is the random perturbation term that may obey a certain distribution. Several other scholars such as [22,26–28] also made contributions to the literatures on the joint pricing and quantity newsvendor problem. Due to the increasing awareness of global warming and climate change, consumers' willingness to buy low carbon products may also increase. The demand on low carbon products is expected to be affected by many factors. Therefore, the production quantity, the amount of carbon emissions, sale price of product and other operational variables should be considered by manufacturers.

Jiang and Chen [29] and Zhang et al. [30] derived the optimal production and carbon emissions for a newsvendor system with consideration of carbon emissions-sensitive random demand and CEP and discussed the impact of carbon emissions-sensitive demand on the manufacturer's operation strategies, total carbon emissions and maximum expected profit. Different from their researches, we assume that manufacturers can trade carbon credits under cap-and-trade, which could also impact manufacturers' decisions. The orthogonal experimental design (OED) is employed to make various reasonable combinations of demand parameters, cost parameters and carbon emissions parameters to capture the non-linear effects on total carbon emissions and expected profit. We compare some recent literatures related to this work in Table 1.

Table 1. Comparisons with recent literatures.

Research Paper	Production Optimization	Carbon Emissions Optimization	CEP	Cap-and-Trade Mechanism
He et al. [14]	Yes	Yes	No	Yes
Du et al. [21]	Yes	No	Yes	Yes
Jiang and Chen [29], Zhang et al. [30]	Yes	Yes	Yes	No
This paper	Yes	Yes	Yes	Yes

3. The Model and Analysis

3.1. Model Description

The manufacturer, which aims at reducing carbon emissions, produces q units of products at the unit cost c. The unit cost does not include the investment cost of carbon emissions reduction. Then the products are sold at the market price p, to meet the uncertain demand D. It is assumed that unsold products will be salvaged at a cost of c_v. Since the investment in carbon emissions reduction has a non-decreasing marginal cost [31–33], we assume that the investment cost function is:

$$I = \frac{1}{2}h\Delta e^2 \ (h > 0) \tag{1}$$

After investing in carbon emissions reduction technologies, the emissions per unit of product is reduced to $e - \Delta e$.

Consumers can buy substitute goods and they are willing to pay for the environmental products, that is, all consumers are homogeneous. The demand is jointly determined by the market sale price and the quantity of the product's carbon emissions reduction, which can be defined using the following equation:

$$D = y(\Delta e) + \varepsilon \tag{2}$$

where $y(\Delta e) = a - p + t\Delta e$. a is the fixed potential market size. $t > 0$, it denotes the impact of emissions reduction on the demand, ε is a random factor with mean μ and variance σ. The probability density function and cumulative density function of ε *is noted as* $f(\cdot)$ and $F(\cdot)$, respectively.

The firm gets an emission cap from the environmental authority. The cap is always the hardest challenge in the cap-and-trade system [21,34]. We assume that a certain emissions cap C_g is imposed by the environmental authority. At the carbon trading center, there is no carbon trading cost and there is no price gap between buy and sell. The market price of carbon credits is determined by the carbon market. The relationship between emissions cap and price of carbon credits is complicated.

In this model, the manufacturer has to determine the production quantity q and the emissions reduction per unit of product Δe, to maximize its expected profit. All the notations are listed in Table 2.

Table 2. Decision variables and parameters.

Decision Variables of Manufacture	
Δe	Emissions reduction per unit of product
Q	Production quantity
Parameters	
a	Potential demand
t	Emissions reduction effectiveness parameter (Erep)
p	Sale price per unit of product
c	Production costs per unit of product
c_v	Salvage value of per unit of unsold product
h	Emissions reduction investment coefficient
e	Initial carbon emissions per unit of product
π_m	Manufacturer's profit
E	Total carbon emissions
p_e	Market price of carbon credits
C_g	Emissions cap

Based on the demand and cost assumptions described above, the manufacturer's expected profit can be computed by the equation below

$$\pi_m = p \cdot E\{\min(D, Q)\} - cQ + c_v E(Q - D)^+ - \frac{1}{2}h\Delta e^2 - p_e\left[(e - \Delta e)Q - C_g\right]. \tag{3}$$

The expected profit includes the revenues from selling in the market, the production cost and the salvage value of the unsold products and the costs of investment in carbon emissions reduction. If the total carbon emissions are more than emissions cap, the last part in Equation (3) represents the carbon trading cost at the market, otherwise, it represents the income from selling the surplus carbon credits.

Let $z = Q - y(\Delta e)$, where $y(\Delta e) = a - p + t\Delta e$. Then we can get $Q = z + y(\Delta e)$, and $(Q-D)^+ = (z-\varepsilon)^+$ Equation (3) can be rewritten as follows:

$$\pi_m = [p - c - p_e(e-\Delta e)][z + y(\Delta e)] - (p - c_v)E(z-\varepsilon)^+ - \frac{1}{2}h\Delta e^2 + C_g p_e, \tag{4}$$

where $E(z-\varepsilon)^+ = \int_A^z F(u)du$.

3.2. Optimal Solutions

In this section, we formulate the extended newsvendor model under cap-and-trade mechanism to derive the optimal solutions and analyze the impacts of the key parameters on the optimal solutions. All proofs are provided in the Appendix A.

Theorem 1. *There exists a unique optimal solution to the model. The optimal decision for the manufacturer is.*

$$\Delta e^* = \frac{p_e(a - p - et + z^*) + t(p-c)}{h - 2tp_e} \tag{5}$$

$$Q^* = z^* + y(\Delta e^*) \tag{6}$$

where $z^* = F^{-1}\left[\frac{p-c-p_e(e-\Delta e)}{p-c_v}\right]$.

From Theorem 1, we first analyze the impacts of the key parameters, that is, h, c, e, t, p_e, on the optimal emissions reduction per unit of product.

Proposition 1. *For any given z,*

(i) *The opftimal Δe^* is non-increasing in h, c and e.*

(ii) *Δe^* is non-decreasing in if $e < \frac{h(a-p+z)+2t^2(p-c)}{th}$, and Δe^* is non-increasing in p_e if $e > \frac{h(a-p+z)+2t^2(p-c)}{th}$.*

(iii) *Δe^* is non-decreasing in t if $e < \frac{2p_e^2(a-p+z)+h(p-c)}{hp_e}$, and Δe^* is non-increasing in t if $e > \frac{2p_e^2(a-p+z)+h(p-c)}{hp_e}$.*

Proposition 1 shows that when the emissions reduction investment coefficient or initial carbon emission which depends on the normal market conditions [12] increases, the manufacturer should invest more to reduce carbon emissions to obtain high efficiency in emissions reduction. Furthermore, if the production cost increases, the manufacturer will pay more to produce products. Therefore, because the investment costs of carbon emissions increases, the manufacturer will gradually be reluctant to invest in reducing carbon emissions over time.

We can also conclude that when p_e and t increase, the optimal emissions reduction per unit of product will not always increase. At low level of initial carbon emissions, the manufacturer has sufficient funds to reduce carbon emissions. In addition, if the market price of carbon credits is high or if consumers have strong willingness to pay more for the sustainable products, the manufacturer will have the motivation to reduce emissions. Then the emissions reduction per unit of product will increase. However, since the marginal investment cost in carbon emissions reduction will increase gradually, the optimal emissions reduction per unit of product will decrease even when both the market price of carbon credits and CEP are high. It indicates that the impact of market price of carbon credits and CEP on optimal carbon emissions reduction per unit of product is based on the normal market's level of carbon emissions reduction.

Proposition 2. *For a given* Δe,

(i) *The optimal production* Q^* *is non-increasing in* h.
(ii) *The optimal production* Q^* *is non-decreasing in* t.
(iii) *The optimal production* Q^* *is non-decreasing in* p_e *if* $0 < e < \frac{2p_e Q + 2t(p-c)}{h}$, *and* Q^* *is non-increasing in* p_e *if* $e > \frac{2p_e Q + 2t(p-c)}{h}$.

Proposition 2 shows that if the carbon emissions reduction investment coefficient increases, the manufacturer should invest more to achieve the previous level of carbon emissions reductions. It means that with the increase of marginal investment costs in carbon emissions reduction, the manufacturer will not pay more for it. To follow carbon regulation and maintain the profit, the manufacturer will choose to reduce production quantity.

It can be concluded that the higher the CEP, the more sustainable products will be produced by the manufacturer. However, with the increase of marginal investment cost, it becomes more difficult to reduce emissions than before. Thus, it occurs that the more the manufacturer produces, the more the total carbon emissions emit even if the emission per unit of product decrease. To maximize profits under carbon constraints, all key parameters should be balanced by the manufacturer.

When p_e increases, the optimal production quantity does not always increase. Under the premise of low initial carbon emissions, the manufacturer has a strong willingness to reduce carbon emissions when the market price of carbon credits is high. On the other hand, when the initial carbon emissions are at a high level, the optimal production quantity will decrease due to the increase of marginal investment cost.

4. Numerical Analysis

In this section, numerical analyses using the orthogonal experimental design are conducted to illustrate the theoretical results shown in previous sections. Software Minitab is used to design the orthogonal experiment.

The initial values of parameters used in this example are set as a = 100, t = 1, p = 4.64, c = 1.16, c_v = 0.87, h = 10, e = 10, C_g = 500 and p_e = 5.8. The demand is assumed to follow a normal distribution with the mean equals 200 and variance equals 0.1. The function of the total carbon emissions is shown as follows:

$$E = (e - \Delta e)Q = (e - \Delta e)[z - (a - p + t\Delta e)]. \tag{7}$$

To test how the cap-and-trade mechanism and the demand information affect the expected profit and total carbon emissions, we use the robust parameter design technique proposed by Taguchi [35]. For a certain carbon emissions reduction technology, the initial emissions and the investment coefficient are determinate. The parameters under tested include cost parameters (p, c, c_v), demand information parameters t and carbon emissions parameters (p_e, C_g). The orthogonal experimental design (OED) was employed to make various reasonable combinations of process parameter levels to capture the non-linear effects on the optimal solutions. There are six parameters at five levels and 25 combinations in the Taguchi orthogonal array (L_{25} 5^6).

Based on the methods proposed by Taguchi [35], we calculate the means of the expected profit and the total carbon emissions using the software Minitab with the options "larger is better" and "smaller is better," respectively.. Each control parameter has five levels. The values for each level are shown in Table 3. Level 3 represents the initial values. Level 1, level 2, level 4 and level 5 represent −50%, −25%, +25% and +50% of the initial values of parameters, respectively, except for emissions reduction effectiveness parameter t, which is set as ±2.5x and ±5x of the initial values. From Appendix B, Table A1 shows the results of the experiment. The first column of Table A1 represents the number of simulation and the subsequent columns represent the process parameters. The rows represent simulations with the levels of each parameter.

Table 3. Values of parameters for each level.

	Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
t	Erep	0.02	0.04	0.2	0.5	1
p	Sale price	2.32	3.48	4.64	5.8	6.96
c	Production costs	0.58	0.87	1.16	1.45	1.74
c_v	Salvage value	0.435	0.6525	0.87	1.0875	1.305
C_g	Emissions cap	250	375	500	625	750
p_e	Carbon credits price	2.9	4.35	5.8	7.25	8.7

From Table A1, we can see that Test No.6 and 11 has the same mean of total carbon emissions while the expected profit of test No.6 is more than that of test No.11. It shows that the expected profits of different combinations of parameter values may be different even the means of total carbon emissions are the same. It indicates that the optimal strategies of the manufacturer and the optimal combination of parameters can be obtained to maximize the expected profit at a certain level of total carbon emissions. Among all tests, Test 6 has the third largest profit and the minimum carbon emissions. Test 5 has the most profits but has more carbon emissions. It means that economic efficiency and environmental benefits are difficult to coordinate. Thus, in a given range of values for the parameters, the results of Test 6 can provide a good reference when manufacturers make decisions.

To obtain the optimal combination of parameter variations, the main effects plots for means of the expected profit and the means of total carbon emissions under cap-and-trade mechanism are shown in Figure 1. We can see that the optimal conditions for maximizing the expected profit are t at level 1, p at level 5, c at level 2, c_v at level 5, C_g at level 4 and p_e at level 5. Figure 1 also demonstrates that the expected profit is non-increasing in the emissions reduction effectiveness parameter. In general, when the consumers have strong willingness to pay more for sustainable products, manufacturers may produce more products to meet the low-carbon demand, which results in more emissions. Then manufacturers should invest in carbon emissions reduction or buy carbon credits from carbon trading market to follow the carbon regulations. However, it is more difficult to reduce carbon emissions because of the increasing marginal investment cost. Therefore, under strict carbon regulation, the expected profit of enterprises will decrease even if the emissions reduction effectiveness parameter increases.

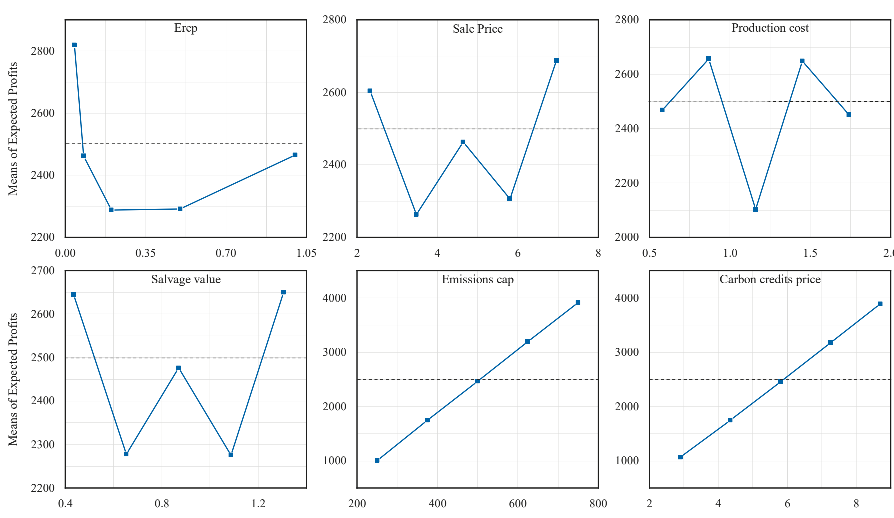

Figure 1. Main effects plot for means of expected profit.

The influence levels of parameters on the mean of expected profit are shown in the response Table 4, where Δ represents the difference between the maximum and minimum values in each column. This table shows that the carbon emissions parameters have larger effect on the expected profit than demand information and cost parameters. Among all parameters, emissions cap has the largest impact on the expected profit, which is followed by the parameters market price of carbon credits and production costs per unit of product parameter. The expected profit increases with the increasing of the former parameter's value and decreases with the increasing of the latter two parameters' values.

Table 4. The response table for means of expected profit under cap-and-trade mechanism.

Level	t Erep	p Sale Price	c Production Costs	c_v Salvage Value	C_g Emissions Cap	p_e Carbon Credits Price
1	2819	2604	2468	2644	1009	1064
2	2462	2263	2656	2278	1746	1750
3	2288	2463	2101	2476	2466	2456
4	2291	2307	2648	2276	3193	3169
5	2465	2688	2451	2650	3911	3886
Δ	531	424	555	375	2902	2822
Rank	4	5	3	6	1	2

According to [36], the unit market price of carbon credits in Beijing's Carbon Trading Center is 5.8 USD/ton. To observe the combined impacts of emissions cap and market price of carbon credits on the expected profit, we assume that each parameter p_e can be modelled using a normal distribution with a mean of 5.8 and a standard deviation of $\sqrt{5}$, that is, p_e~N (5.8, 1). C_g is assumed to range from 200 to 1000. Figure 2 shows that when the market price of carbon credits fluctuates, the expected profit will increase if the emissions cap increases.

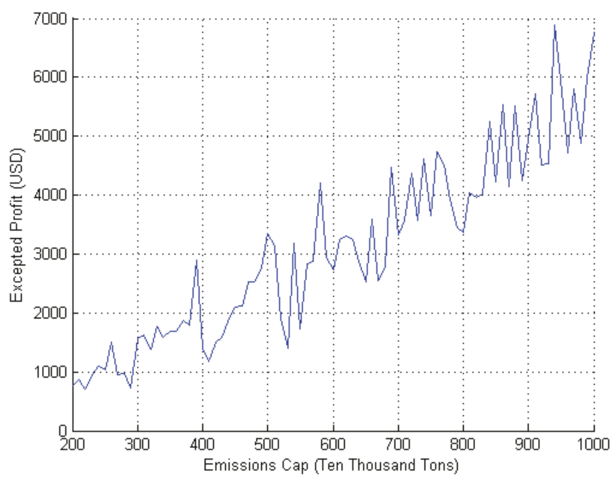

Figure 2. Effect of carbon emissions cap on the excepted profit.

As analyzed above, carbon emissions cap, carbon trading market and CEP have the largest impact on the manufacturer's expected profit. When the government allocate more free carbon credits or the market price of carbon credits is high, the manufacturer will have motivations to reduce carbon emissions and sell surplus carbon credits to gain extra revenue. The values of other parameters should be carefully dealt with to trade off the maximal expected profit and minimal carbon emissions.

The main effects of all parameters on the mean of total carbon emissions and the optimal combinations of parameter variation can be observed in Figure 3. The optimal conditions for minimizing carbon emissions are t at level 1, p at level 1, c at level 5, c_v at level 4, C_g at level 1, p_e at level 5. It can be seen that the mean of total carbon emissions is non-increasing in the market price of carbon credits but is non-decreasing in the sale price per unit of product. When the emissions reduction effectiveness parameter increases, the mean of total carbon emissions also increases. Manufacturers will produce more products to meet the low-carbon demand. In this case, if manufacturers do not reduce carbon emissions, the government will take more strict carbon regulations on manufacturers with larger emissions.

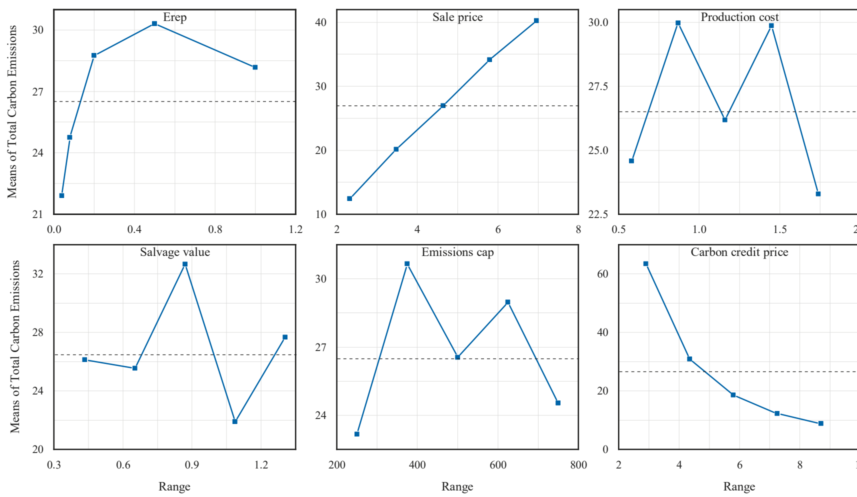

Figure 3. Main effects plot for means of total carbon emissions.

The influence level of every parameter on the joint production and carbon emissions reduction newsvendor problem for means of total carbon emissions is presented in Table 5, where Δ represents the difference between the maximum and minimum values in each column. Among all parameters, the market price of carbon credits has strongest effect on the total carbon emissions. It is followed by the sale price per unit of product and the emissions reduction effectiveness parameter. From Table 5, we can see that the cost parameters have higher impact on the carbon emissions than the emissions cap.

Table 5. The response table for means of total carbon emissions under cap-and-trade mechanism.

Level	t Erep	p Sale Price	c Production Costs	c_v Salvage Value	C_g Emissions Cap	p_e Carbon Credits Price
1	21.908	12.410	24.577	26.127	23.165	63.441
2	24.753	20.110	29.967	25.546	30.660	30.867
3	28.755	26.978	26.179	32.659	26.549	18.498
4	30.298	34.133	29.862	21.890	28.965	12.241
5	28.167	40.249	23.295	27.658	24.542	8.833
Δ	8.390	27.839	6.672	10.769	7.495	54.608
Rank	4	2	6	3	5	1

According to [36], the unit market price of carbon credits in Beijing's Carbon Trading Center is 7.26 USD/ton. To study the relationship between market price of carbon credits and the carbon emissions in more detail, the market price of carbon credits is assumed to vary from 0.72 USD/ton to 9.42 USD/ton. Figure 4 shows that when the market price of carbon credits is less than 3 USD/ton, the carbon emissions will decrease at a high rate. When the market price of carbon credits is greater than 3 USD/ton, it is difficult for the manufacturer to reduce carbon emissions due to the technical limitations and the increase of marginal investment costs. This directly results in low efficiency of carbon emissions reduction. Therefore, the manufacturer is inspired to invest in carbon emissions reduction to sell their surplus quotas at high market price to gain extra revenue. However, the speed of emissions reduction will become slow due to the investment in carbon emissions reduction has an increasing marginal cost, even there are sufficient carbon credits available on the market. It indicates that many manufacturers will choose to sell the surplus carbon credits by reducing carbon emissions to gain more profit when the market price of carbon credits is high. In a certain range, the higher the carbon price, the less the carbon emissions.

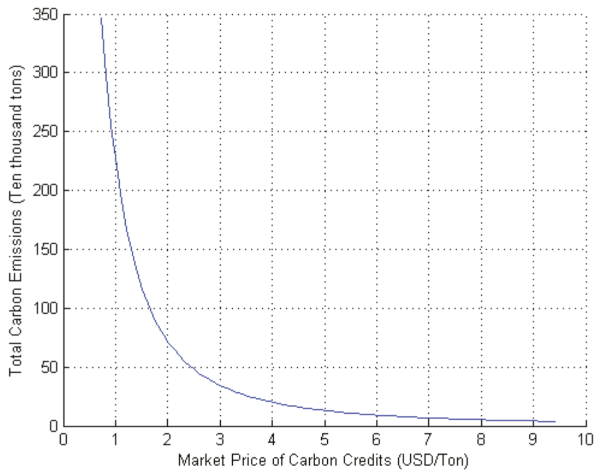

Figure 4. Effect of market price of carbon credits on carbon emissions ($0.72 \leq p_e \leq 9.42$).

In summary, the emissions cap has little effect on the total carbon emissions. No matter how many free carbon credits are allocated by the government, the total carbon emissions are mostly affected by carbon trading price and market sale price of product. That is to say, the carbon trading market and product market play more major role than the government in regulating manufacturers. When manufacturers make optimal strategies, they should consider more about the CEP and their funding conditions. Therefore, all key parameters should be considered to trade off the expected profit and carbon emissions and to obtain the multi-period global optimal solutions [20].

By using OED, the influence of carbon policies, consumers' environmental preference and cost variables on manufacturers' expected profits and total carbon emissions are examined. There are several important policy implications:

(1) When the market price of carbon credits increases, the expected profit will increase and the carbon emissions will decrease. However, the trend will be flat over time. When the carbon trading price is low, the efficiency of reducing carbon emissions is also low. It indicates that high market price of carbon credits is not always good for reducing emissions.

(2) When the CEP increases, the excepted profit will decrease and the total carbon emissions will decrease first and then increase. The manufacturer will produce more products to meet the increasing low-carbon demand. In general, carbon emissions increase as production increases. To control the carbon emissions and follow the carbon policies, manufacturers need to buy quotas or invest in carbon emissions reduction [12]. However, it will become difficult for manufacturers to reduce emissions due to the increasing marginal investment cost. This will lead to more carbon emissions over time. Thus, it is critical that manufacturers should response timely based on demand information, such as CEP. Our model could be applied to help manufacturers make optimal solutions at any time.

(3) When the carbon cap is high, the expected profits of manufacturers will increase. It indicates that under loose carbon regulation, there are sufficient carbon quotas. The manufacturers could benefit from selling the carbon credits instead of investing in carbon emissions reduction.

(4) When the market sale prices of low-carbon products increase, there will be few consumers buy the products. Due to the increasing marginal produce cost and marginal investment cost, manufacturers will not use the cleaner/low-carbon technologies and they will produce regular products, which lead to higher carbon emissions. Therefore, the pricing-setting of products is important and has great effects on total carbon emissions.

5. Conclusions and Future Perspectives

Among many carbon regulations, the cap-and-trade mechanism has incentivized the reduction of carbon emissions. Manufacturers should re-determine their operation polities. This study extended the newsvendor model to derive the optimal production quantity and carbon emissions reduction for manufacturers. Especially, the manufacturers face a market with random demand that is mainly impacted by the emissions reduction per unit of product. Numerical examples are provided to develop the robustness of system parameters via the orthogonal experimental design technique. The results show that when customers are sensitive to the emissions reduction per unit of product, more manufacturers will quickly invest in carbon emissions reduction to increase revenue. Furthermore, manufacturers are willing to invest in carbon emissions reduction when the market price of carbon credits and CEP are high. However, it will become more difficult to reduce emissions due to the increasing marginal abatement cost. On the other hand, manufacturers will not be motivated to take measures to reduce carbon emissions when the free carbon quotas allocated by the government is sufficient. Therefore, it is critical that the government sets reasonable carbon emissions cap. In summary, the carbon trading parameters, cost parameters and the demand-related parameters can impact the optimal strategies. Manufacturers should trade off all parameters to maximize their profits and minimize carbon emissions. The government should make their policies.

There are several interesting extensions to this work. In this study, we assume that (1) manufacturers sell products to consumers directly without cooperation between their upstream and downstream enterprises and (2) all low-carbon products have the same carbon emissions and have the same effects on the market. However, since the manufacturers and consumers are heterogeneous, more nuanced models can be developed to understand market behavior. In a real market, carbon credits can be saved and can be transferred for use in the next production period. Another set of models could be developed to identify how a manufacturer should choose to sell carbon credits or to invest in additional reduction technology to save carbon credits. These methods could help both governments and manufacturing industries to understand how market conditions change and make better long-term decisions.

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Appendix A

Proof of Theorem 1. The solution for z^* and Δe^* in Equations (5) and (6) are optimal if the Hessian $E[\pi_m(z^*, \Delta e^*)]$ is negative semi definite where the Hessian is given by $\begin{bmatrix} -(p-c_v)f(z) & p_e \\ p_e & 2tp_e - h \end{bmatrix}$.

$H_1 = -(p - c_v)f(z)$ which is always negative. If condition $H_2 = (h - 2tp_e)(p - c_v)f(z) - p_e^2 > 0$ is satisfied, $E[\pi_m(z^*, \Delta e^*)]$ is a concave function of z^* and Δe^*. Equation (4) exists the unique optimal solution. To solve the result, then:

$$\frac{\partial E[\pi_m]}{\partial z} = [p - c - p_e(e - \Delta e)] - (p - c_v)F(z), \tag{A1}$$

$$\frac{\partial E[\pi_m]}{\partial \Delta e} = p_e[z + y(\Delta e)] + t[p - c - p_e(e - \Delta e)] - h\Delta e. \tag{A2}$$

Let $\frac{\partial E[\pi_m]}{\partial z} = 0$, $\frac{\partial E[\pi_m]}{\partial \Delta e} = 0$, we could gain z^* and Δe^*. According to the relationship between z and Q, the optimal production quantity can be presented by the following equation:

$$Q^* = z^* + y(\Delta e^*) \tag{A3}$$

The Theorem is proved. □

Proof of Proposition 1. From Theorem 1, the optimal solution Δe^* is presented as follows:

$$\Delta e^* = \frac{p_e(a - p - et + z) + t(p - c)}{h - 2tp_e}. \tag{A4}$$

It is clear to see that Δe^* is decreasing with h, e and c. In order to observe the effect of market price of carbon credits on the optimal quantity of carbon emissions reduction, the best response function of the retailers from the first derivative for p_e of Δe^* is shown as follows:

$$\frac{\partial \Delta e^*}{\partial p_e} = \frac{h(a - p + z - et) + 2t^2(p - c)}{(h - 2tp_e)^2}. \tag{A5}$$

If $e < \frac{h(a-p+z)+2t^2(p-c)}{th}$, we can get $\frac{\partial \Delta e^*}{\partial p_e} > 0$, which indicates that Δe^* is increasing in p_e. If $e > \frac{h(a-p+z)+2t^2(p-c)}{th}$, there always have $\frac{\partial \Delta e^*}{\partial p_e} < 0$, which indicates that Δe^* is decreasing in p_e.

On the other hand, the best response function of the retailers from the first derivative for t of Δe^* is shown as follows:

$$\frac{\partial \Delta e^*}{\partial t} = \frac{2p_e^2(a - p + z) + h(p - c - ep_e)}{(h - 2tp_e)^2} \tag{A6}$$

When $e < \frac{2p_e^2(a-p+z)+h(p-c)}{hp_e}$, we can get $\frac{\partial \Delta e^*}{\partial t} > 0$, which indicates that Δe^* is increasing in t. When $e > \frac{2p_e^2(a-p+z)+h(p-c)}{hp_e}$, we can know that $\frac{\partial \Delta e^*}{\partial t} < 0$, which indicates that Δe^* is decreasing in t.

The Proposition is proved. □

Proof of Proposition 2. Theorem 1 shows the optimal solution Δe^* and z^* which could be presented as follows:

$$(h - 2tp_e)(p - c_v)F(z^*) = (h - tp_e)(p - c - ep_e) + p_e^2(a - p + z) \tag{A7}$$

We take the derivative of z^* with respect to h,

$$\frac{\partial z^*}{\partial h} = \frac{-p_e\Delta e}{(h - 2tp_e)(p - c_v)f(z) - p_e^2} < 0 \tag{A8}$$

Because of $\frac{\partial Q^*}{\partial h} = \frac{\partial z^*}{\partial h} < 0$, the optimal production Q^* is decreasing in h.

We take the derivative of z^* with respect to t,

$$\frac{\partial z^*}{\partial t} = \frac{p_e(p - c_v)F(z) + \Delta e p_e^2}{(h - 2tp_e)(p - c_v)f(z) - p_e^2} > 0 \tag{A9}$$

According to Equation (A3) $\frac{\partial Q^*}{\partial t} = \frac{\partial z^*}{\partial t} > 0$. Then we take the first derivative of z^* and Q^* with respect to p_e,

$$\frac{\partial Q^*}{\partial p_e} = \frac{\partial z^*}{\partial p_e} = \frac{t(p-c) + 2p_e(a - p + z^* + t\Delta e) - eh}{(h - 2tp_e)(p - c_v)f(z^*) - p_e^2} = \frac{t(p-c) + 2p_e Q^* - eh}{(h - 2tp_e)(p - c_v)f(z^*) - p_e^2} \quad \text{(A10)}$$

when $e < \frac{2p_e Q + t(p-c)}{h}$, there always have $\frac{\partial Q^*}{\partial p_e} > 0$. Otherwise, we can know $\frac{\partial Q^*}{\partial p_e} < 0$.

The Proposition is proved. □

Appendix B

Table A1. The expected profit and total carbon emissions under cap-and-trade mechanism.

No.	t	p	c	c_v	C_g	p_e	$mPro^*$	E^*
1	1	1	1	1	1	1	283	38
2	1	2	2	2	2	2	1189	25
3	1	3	3	3	3	3	2456	19
4	1	4	4	4	4	4	4087	15
5	1	5	5	5	5	5	6080	13
6	2	1	2	3	4	5	4953	4
7	2	2	3	4	5	1	1753	47
8	2	3	4	5	1	2	658	29
9	2	4	5	1	2	3	1741	24
10	2	5	1	2	3	4	3206	20
11	3	1	3	5	2	4	2234	4
12	3	2	4	1	3	5	3870	6
13	3	3	5	2	4	1	1412	63
14	3	4	1	3	5	2	2876	42
15	3	5	2	4	1	3	1048	29
16	4	1	4	2	5	3	3863	7
17	4	2	5	3	1	4	1334	8
18	4	3	1	4	2	5	2805	9
19	4	4	2	5	3	1	1110	78
20	4	5	3	1	4	2	2343	49
21	5	1	5	4	3	2	1687	9
22	5	2	1	5	4	3	3171	14
23	5	3	2	1	5	4	4983	14
24	5	4	3	2	1	5	1720	12
25	5	5	4	3	2	1	763	91

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A Circular Economy Approach to Military Munitions: Valorization of Energetic Material from Ammunition Disposal through Incorporation in Civil Explosives

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Abstract: Ammunition that has reached its end of life or become obsolete is considered hazardous waste due to the energetic material content that must be decommissioned. One of the technologies to dispose of ammunition involves the use of incinerators with sophisticated gas treatment systems; however, this disposal process has important limitations in terms of incinerator capacity, energy requirements and high costs. This article assesses the potential primary energy avoided and environmental benefits arising from the valorization of energetic material from military ammunition by incorporating it into civil emulsion explosives, as an alternative to destructive disposal. This approach follows the circular economy principle, as articulated *inter alia* in BS 8001:2007, by giving a new service to a residue through its incorporation into a new product. A prospective life-cycle model is implemented based on primary data from previous studies on the conventional disposal process and on the production of emulsion explosive. The model applies system expansion to calculate the environmental burdens avoided when energetic material from ammunition is incorporated into civil explosives. The results show that re-using ammunition through valorization of energetic material greatly reduces the environmental impacts in all categories compared to the conventional disposal process. The benefits arise mainly from avoiding the incineration and flue gas treatment processes in ammunition disposal, and displacing production of civil explosive components with the energetic material from ammunition.

Keywords: ammunition incineration; down-cycling; energetic material recycling; industrial ecology; life-cycle assessment

1. Introduction

Armed Forces possess significant quantities of military munitions that need to be disposed of when they reach their end-of-life or become obsolete. Energetic materials such as propellants and explosives, which are complex and expensive chemical substances, are regularly sent for disposal when the ammunition in which they are contained is decommissioned. The exact quantity of munitions that need to be disposed of is difficult to ascertain. Since 2008, NSPA (NATO Support and Procurement Agency) have awarded 39 demilitarization contracts for disposal of munitions that amounted to a total of approximately 400 million euros [1]. The stockpile of munitions to be decommissioned in the United States in 2010 has been estimated to as 450,000 metric tons [2]. Other parts of the world also have significant amounts of munitions for disposal which, in addition to safety hazards, present a security problem due to the potential for use in terrorist activities [3].

In Portugal, the disposal of munitions has been an important issue due to the significant stock of obsolete munitions, which usually have to be stored for long periods of time before being incinerated in small batches in plant with limited capacity [4]. The disposal of munitions is carried out by the company idD, which decommissions approximately 550 metric tons of munitions per year, of which 80 metric tons are energetic material [4]. The problem of munitions disposal is not unique to Portugal so that, although the results presented here refer to Portugal, the conclusions are general.

Disposal of ammunition needs to be carried out under secure conditions and with minimum environmental impact, which makes it an onerous process with costs estimated as approximately 1600 USD per metric ton of munition [5]. Currently, most of the energetic material discharged from ammunition is disposed of in incinerators with gas treatment systems. However, use of such combined elimination systems is limited by the available capacity, energy requirements and costs of operation and maintenance. Ferreira et al. [6] assessed the environmental impacts of the disposal process in Portugal and demonstrated significant burdens associated with incineration and gas treatment, primarily due to high consumption of electricity and propane.

The energetic material in obsolete ammunition is frequently in usable condition with significant value. However, direct re-use for military purposes is not viable due to highly demanding safety standards and the resultant high costs of re-use. Therefore, instead of consuming energy to destroy the material, at least some of its value should be recovered by down-cycling into other uses. The solution explored here is based on incorporating energetic material into ammonium nitrate-based emulsion explosives (a common type of civil explosive used for mining and construction). This approach would not only avoid incineration and its inherent environmental impacts but would also reduce the impacts associated with production of the civil explosive by partial displacement of the emulsion matrix components. As this process entails down-cycling a residue into a new product to provide a new function, it follows the circular economy principle, for example as articulated in BS 8001 [7].

Previous experimental work has shown the feasibility of blending energetic material (powders and TNT) into ammonium nitrate (AN) based emulsion explosives. Ribeiro et al. [8] studied the behavior of emulsion explosives incorporating different types of energetic materials (e.g., single and double based powders, and TNT) and concluded that up to 20% w/w of any of these materials can be incorporated without forming any new chemical species. This indicates a good range of chemical compatibility between the emulsion explosive and energetic materials from munitions. However, these amounts of energetic material caused a slight increase in the detonation velocity and in the shock sensitivity. These changes can be reduced to an acceptable level, and eventually removed completely, by reducing the energetic material content sufficiently. Ribeiro et al. [8] also demonstrated that a simple processing technique such as grinding is necessary, but sufficient, to allow the incorporation of the energetic materials in the emulsion explosive matrix. The potential advantages of recycling energetic materials have been highlighted [9], but there appears to be no published work that has attempted to quantify the environmental benefits of down-cycling the energetic material into other uses. Down-cycling of energetic material is currently carried out by companies that have contracts for both elimination of munitions and production of civil explosives. However, for companies that just focus on one of these businesses, there are barriers to adopting this approach, particularly in countries where the quantities of munitions demilitarized are small. Production of civil explosive incorporating down-cycled energetic material requires supplementary quality control. It may not be economically attractive to develop a new market centered on the production of a new type of civil explosive unless enough energetic material is available. This limitation could hinder development of a circular economy in energetic material from munitions.

The main goal of this article is to calculate the potential primary energy use avoided and environmental benefits arising from the incorporation of energetic material from military ammunition into ammonium nitrate-based emulsion explosives, as an alternative to conventional ammunition disposal. The assessment allows for displacement of both incineration of the energetic materials and production of the equivalent matrix components of an emulsion explosive, using system expansion to avoid allocation by assigning the avoided environmental burdens to the function of managing the military explosive.

2. Materials and Methods

In this section, the life-cycle model and the inventory developed for both the conventional process and the proposed closed-loop process are described. First, the current approach to disposal of military ammunition is presented. The prospective LCA is then set out, covering recycling of the energetic material including production of civil explosives, using system expansion to avoid allocation across the multiple functions. The life-cycle model, the life-cycle inventory, and the calculation of the life-cycle impacts were conducted using the Simapro 8.0 software [10]. As in other LCA studies, a number of assumptions and simplifications were necessary; in this study, they were required due to the lack of available data for the novel recycling processes (e.g., electricity consumption for grinding the recycled energetic material, and for mixing it into the emulsion explosive product). Another limitation is the static nature of the LCA: Changes such as technological evolution and introduction of new materials have not been considered.

2.1. Conventional Decommissioning of Military Ammunition

Figure 1 shows a simplified flowchart of the conventional process to dispose of military ammunition, including information associated with inputs and outputs. Disposal of military ammunition encompasses:

(i) dismantling of ammunition to separate the different components (e.g., cartridge, projectile, fuse);
(ii) energetic material unloading in which powders and high explosives are withdrawn from the cartridge and the warhead;
(iii) separation of inert materials (e.g., metals, plastics, electronics) from the ammunition components;
(iv) incineration of the energetic materials in a static kiln; and
(v) treatment of the gases resulting from the incineration.

The Life-Cycle Inventory (LCI) was implemented based on detailed data from idD, the company responsible for ammunition disposal in Portugal. This inventory is also representative of the typical disposal of energetic material in other countries. It includes the impacts associated with generating the energy consumed (electricity and propane), supplying water and chemicals for the gas treatment process, and the emissions associated with combustion (or thermal degradation) of the energetic materials as well as combustion of the propane in a post-combustion chamber. Unusually for LCA, manufacture and transport of equipment was also included in the inventory (information provided by idD) as the incineration is an intensive batch process with limited equipment service life. The functional unit was defined as 1 kg of TNT equivalent of energetic material disposed. More detailed information and analysis of this process are given in Ferreira et al. [6].

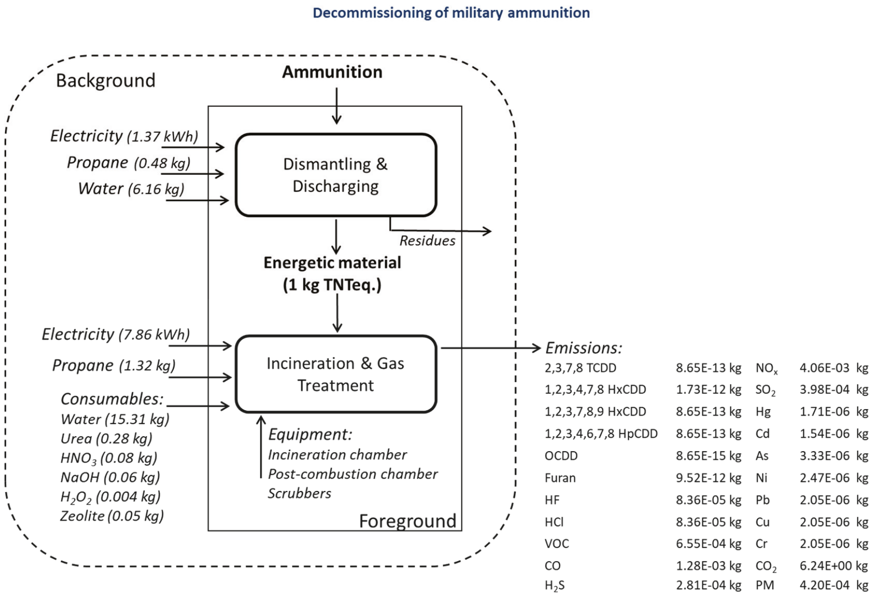

Figure 1. Simplified flowchart for conventional disposal of 1 kg TNTeq of energetic material from military ammunition.

2.2. Recycling Energetic Material

Figure 2 shows the flowchart for a possible process to dispose of explosives in ammunition by recycling (more strictly, down-cycling) into emulsion explosives, including information associated with the main inputs and outputs. This process includes dismantling (carried out as described above for conventional disposal) to separate the different ammunition components and unload the energetic material. Dismantling generates a range of energetic materials, in different forms (e.g., prills, sticks, particles and flakes), so it is necessary to grind each of these materials and blend them to yield a consistent final product that can be incorporated into the emulsion explosive. An energy consumption of 0.9 kWh per kg TNT equivalent for the grinding process is estimated, based on the power of the grinder and the grinding time. It is assumed, based on primary evidence, that material losses in grinding and incorporating the energetic material in the emulsion explosive are negligible. The use phase of the emulsion explosive is not included in the analysis, because once the energetic material has been incorporated in the emulsion explosive its life-cycle no longer differs from the base case (the standard emulsion explosive) with which it is compared. It should be noted that the proportion of down-cycled material ($< 20\%$) added to the standard emulsion is small and does not influence the performance of the civil explosive. Information on the life-cycle impacts associated with the production of civil explosives is needed to assess the impacts avoided by down-cycling the energetic material. LCI data for conventional production of the emulsion explosive are taken from Ferreira et al. [11], covering transport of raw material, emulsification, sensitization and packaging, based on detailed process data provided by a European company. The constituents of the emulsion matrix were ammonium nitrate, water, mineral oil and an emulsifier (Polycarboxylate), together with hollow microspheres of extruded polystyrene (XPS) included as a sensitizing agent. The energy used in the process—electricity and light fuel oil—was also included in the inventory.

The ground energetic material is incorporated into the emulsion matrix, displacing an equivalent amount of ammonium nitrate, mineral oil and emulsifier, before the resulting mixture is sensitized by adding hollow polymer microspheres. Due to lack of data for this specific operation, the energy consumption in producing the mixed emulsion was assumed to be equal to that for the conventional process.

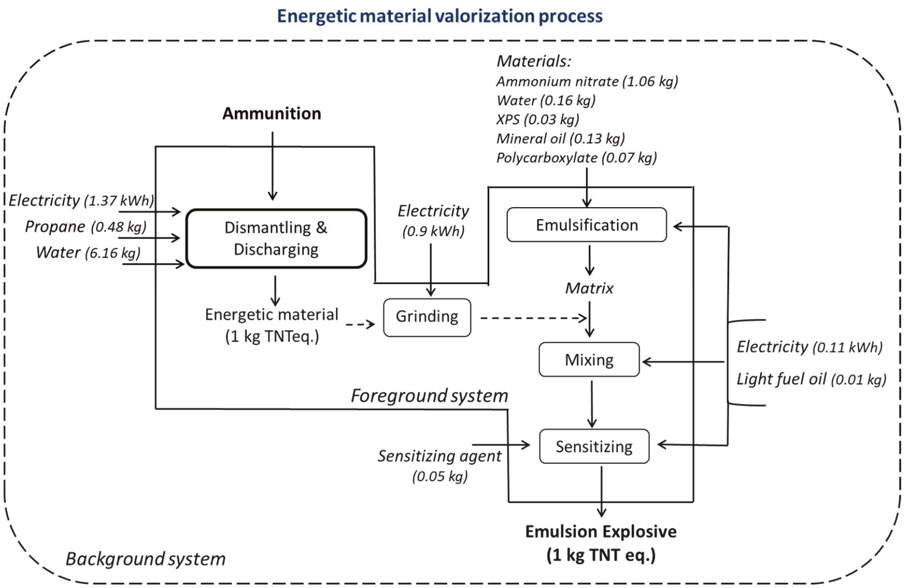

Figure 2. Simplified flowchart for valorization of 1 kg TNTeq of energetic material by incorporation into civil explosive.

Incorporation of the energetic material from military ammunition into civil explosives is a possible way to valorize a waste that otherwise would be incinerated with significant energy consumption and environmental impacts. This constitutes a multifunctional process. The primary function is still to dispose of military ammunition, so the functional unit is defined as disposal of 1 kg of TNT equivalent of energetic material from ammunition. However, the process also provides the function of producing 1 kg of TNT equivalent of emulsion explosive. The multifunctionality is handled according to the approach recommended in ISO 14040 [12], following common practice for recycling and down-cycling of pre-existing waste (e.g., [13–17]): System expansion is used to avoid allocation by including the extra function, i.e., production of 1 kg of TNT equivalent of civil explosive [18,19].

Expanding the system in this way accounts for the two modifications to the conventional ammunition disposal process, as shown in Figure 3: (i) avoiding the incineration and flue gas treatment process associated with the ammunition disposal; and (ii) displacing production of emulsion explosive matrix. The environmental advantages of down-cycling rather than disposal are then represented by:

$$\begin{array}{c}\text{Avoiding incineration and gas cleaning}\\ +\\ \text{Displacing production of emulsion explosive}\\ -\\ \text{Grinding energetic material from military ammunition.}\end{array} \quad (1)$$

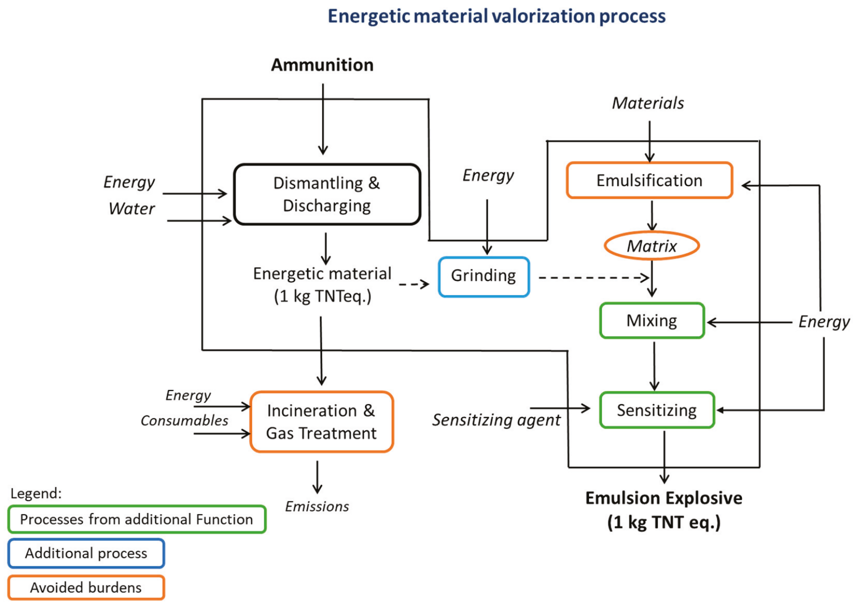

Figure 3. Simplified flowchart to show the additional functions and avoided burdens associated with recycling of 1 kg TNTeq of energetic material by incorporation into civil explosive.

2.3. Life-Cycle Impact Assessment Methods

Life-cycle impact assessment provides additional information by converting the inputs and outputs comprising the inventory data into quantified potential environmental impacts [20] using characterization factors for specific impact categories. Two general approaches to impact characterization have been developed: Problem-oriented (mid-point categories) or damage-oriented (end-point categories) [21]. For this study, the mid-point approach was used as the results have the advantage of lower uncertainty associated with the cause-effect chain between the inventory and the potential impacts compared to end-points. For this assessment, the CML problem-oriented method was employed, because it is widely accepted as a reliable way to assess the impacts and also because previous studies to evaluate the impacts of demilitarization of ammunition [6] and production of civil explosive [11] also employed this method. The six environmental impact categories selected as most significant here are summarized in Table 1 [22]. In addition to the environmental impacts in Table 1, one category for the non-renewable primary energy and three toxicological impact categories (human toxicity with cancer and non-cancer effects, and ecotoxicity) have been considered. The non-renewable primary energy was calculated by the CED (cumulative energy demand) method [22]. The toxicological impacts were estimated using the USEtox model for the cause-effect chain. Two sets of characterization factors are available: 'recommended' factors derived from the most widely used version of USEtox; and 'interim' factors derived from a version of USEtox modified with the aim of providing a better description of the cause-effect chain for metals, amphiphilic, and ionic substances. This work is based on the 'recommended' characterization factors because they are more widely used, pending assessment of the reliability of the 'interim' factors [23].

Table 1. Description of impacts considered: Non-renewable primary energy use (CED method), six environmental impact categories (CML method) and three toxicological impact categories (USEtox method), adapted from [22].

Impact Category	Description	Unit
Non-renewable Primary Energy	Primary energy considering various energy sources	MJ prim.
Abiotic Depletion (AD)	Determine the extraction of minerals and fossil fuels, based on concentration of reserves and rate of de-accumulation	kg Sb eq
Acidification (Acid)	Describes the fate and deposition of acidifying substances	kg SO_2 eq
Eutrophication (Eut)	Describes the impacts due to excessive levels of macronutrients in the aquatic environment	kg $PO_4{}^{3-}$ eq
Global Warming (GW)	Describes the impacts associated with emissions of greenhouse gases	kg CO_2 eq
Ozone Layer Depletion (OLD)	Defines the impacts from the emission of gases that have an effect in the destruction of the stratospheric ozone layer	kg CFC-11 eq
Photochemical Oxidation (OP)	Describes the creation of reactive substances (mainly ozone)	kg C_2H_4 eq
Human Toxicity Cancer (HT, cancer)	Describes the cancer effects of chemical emissions on human health	cases
Human Toxicity Non-cancer (HT, non-cancer)	Describes the non-cancer effects of chemical emissions on human health	cases
Ecotoxicity	Describes the effects of chemicals on ecosystems	PAF.m^3.day

PAF—potentially affected fraction of species.

Normalization is an optional further step in which the estimated life-cycle impacts of a product or service are expressed as fractions of the impacts associated with a reference activity or situation [24]. The normalized values show the relative significance of the different mid-point impacts [20]. In this work, the environmental impacts were normalized with respect to the total impact of the EU25+3 economy for the year 2000 [25]. Details of the normalization process and normalized results are given in the Appendix A (Figures A1 and A2).

3. Results and Discussion

3.1. Life-Cycle Impact Results

Life-Cycle Impact Assessment results associated with the recycling of the energetic material are presented in this section. The full comparison between the impacts for conventional ammunition disposal by incineration and valorization of energetic material is reported in Figure 4. Comparison between the two approaches shows that down-cycling energetic material from munitions significantly decreases all impacts; the main benefits arise from avoiding incineration and gas cleaning for the conventional process, and also transport and production of the emulsion explosive matrix. The grinding process, an operation specific to the new approach, presents a nugatory contribution to the life-cycle impacts in all categories.

The normalized results help in selecting the most important impact categories, to facilitate analysis of the potential benefits of recycling energetic material into civil explosives. The most significant environmental impact categories emerge as Eutrophication, Acidification, and Global Warming; while the most significant toxicological impact category is Human Toxicity with cancer effects. The following discussion is presented in terms of these four impact categories but, for the particular case assessed here, the overall conclusions are also supported by the other environmental and toxicological impacts.

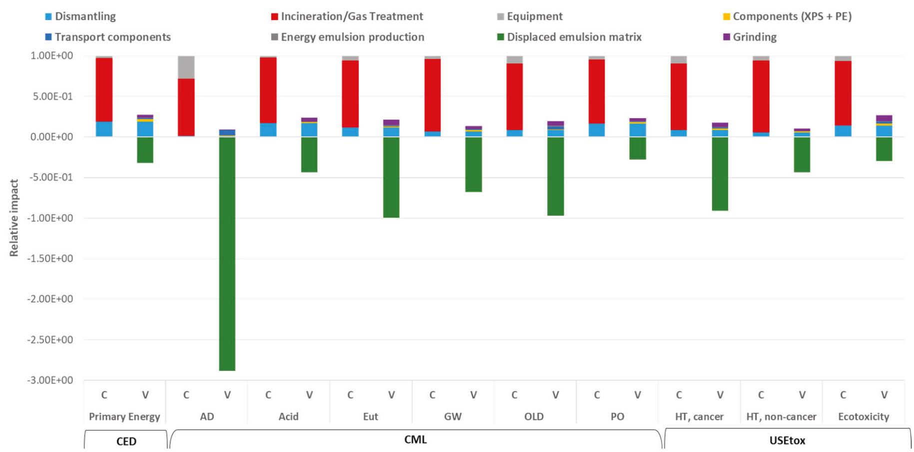

Figure 4. Comparison between the impacts per kg TNT eq associated with conventional ammunition disposal by incineration (C) and with down-cycling of energetic material from ammunition into civil explosives (V).

Table 2 shows the contributions to the four dominant impact categories of the main processes associated with conventional disposal and down-cycling into civil explosives. Dismantling is common to both processes, along with final use, so the comparison depends on incineration and production of the civil explosives. The impacts for conventional disposal are dominated by the incineration and gas treatment process, mainly due to the electricity required (whose contribution ranges from 35% of Global Warming to 80% of Ecotoxicity). Down-cycling of energetic material from munitions avoids these processes, resulting in a decrease of the environmental impacts by approximately 80%. These savings result from the high energy requirement of the incineration and flue gas treatment operations in the conventional disposal process, arising from the need to heat the batch-operated kiln and maintain it at the required temperature (400 °C to 600 °C) as well as to operate the equipment used in treating the flue gas to ensure acceptably clean emissions (post-combustion chamber, selective catalytic reduction systems, and scrubbers). Moreover, for safety reasons, the static kiln only operates with small batches of energetic material (up to 20 kg TNT equivalent per hour); this increases its operating time and specific energy consumption.

The impacts avoided by displacing production of the emulsion matrix are also noteworthy. In fact, the avoided burdens associated with the production and transport of the matrix components (principally ammonium nitrate, which alone contributes more than 75% of the total impact) are similar to or higher than the life-cycle impacts resulting from the dismantling of munitions. Producing the constituent components accounts for more than 80% of the total impacts for production of emulsion explosive [11], so it is not surprising that the displacement of these components presents a substantial benefit. As a result, the benefits from displacing the emulsion explosive matrix alone are enough to make down-cycling of energetic material from military munitions desirable from an environmental perspective.

As noted above, the additional energy required to grind the energetic material for incorporation into the emulsion explosive matrix is nugatory in comparison with the other impacts: Representing less than 8% of the total life-cycle impacts. Therefore, the grinding process is not an obstacle to down-cycling of energetic material from military munitions.

Table 2. Contribution to environmental life-cycle impacts of conventional ammunition disposal and down-cycling of energetic material from ammunition (per kg TNTeq.).

Processes		Eut (kg PO_4^{-3} eq)		Acid (kg SO_2 eq)		GW (kg CO_2 eq)		HT, Cancer (Cases)	
		Conventional Disposal	Recycling	Conventional Disposal	Recycling	Conventional Disposal	Recycling	Conventional Disposal	Recycling
Decommissioning	Dismantling	1.56×10^{-3}	1.56×10^{-3}	1.53×10^{-2}	1.53×10^{-2}	9.76×10^{-1}	9.76×10^{-1}	4.12×10^{-11}	4.12×10^{-11}
	Incineration/gas Treatment	1.13×10^{-2}	0.00×10^{0}	7.26×10^{-2}	0.00×10^{0}	1.27×10^{1}	0.00×10^{0}	3.82×10^{-10}	0.00×10^{0}
	Equipment	7.70×10^{-4}	0.00×10^{0}	1.88×10^{-3}	0.00×10^{0}	5.27×10^{-1}	0.00×10^{0}	4.25×10^{-11}	0.00×10^{0}
Emulsion explosive production	Components	0.00×10^{0}	2.04×10^{-4}	0.00×10^{0}	9.63×10^{-4}	0.00×10^{0}	2.46×10^{-1}	0.00×10^{0}	7.26×10^{-12}
	Transport of components	0.00×10^{0}	8.76×10^{-5}	0.00×10^{0}	3.71×10^{-4}	0.00×10^{0}	1.37×10^{-1}	0.00×10^{0}	5.47×10^{-12}
	Energy	0.00×10^{0}	1.26×10^{-4}	0.00×10^{0}	5.44×10^{-4}	0.00×10^{0}	6.77×10^{-2}	0.00×10^{0}	3.18×10^{-12}
	Displaced emulsion matrix	0.00×10^{0}	-1.36×10^{-2}	0.00×10^{0}	-3.91×10^{-2}	0.00×10^{0}	-9.61×10^{0}	0.00×10^{0}	-4.23×10^{-10}
Grinding		0.00×10^{0}	9.72×10^{-4}	0.00×10^{0}	4.00×10^{-3}	0.00×10^{0}	5.09×10^{-1}	0.00×10^{0}	2.50×10^{-11}
Total		1.36×10^{-2}	-1.06×10^{-2}	8.89×10^{-2}	-1.78×10^{-2}	1.42×10^{1}	-7.68×10^{0}	4.65×10^{-10}	-3.41×10^{-10}

3.2. Scenario Analysis: Influence of Electricity Mix

The results summarized above show that the environmental impacts from decommissioning of military explosives depend strongly on the high energy requirements of the incineration and gas treatment processes, and hence on the environmental impacts associated with generation and distribution of electricity. To gauge the generality of the conclusions on the benefits of down-cycling, a comparative assessment was carried out to compare the impacts in Portugal with three other electricity mixes—USA, China and Sweden. The environmental impacts of the electricity mixes considered here are based on data from the year 2008 [26,27]. However, the specific cases are not critical because the purpose of the scenario analysis is to explore a wide spectrum of different energy sources.

Figure 5 compares the impacts for incineration of ammunition in a static kiln using the different electricity mixes for the four dominant impact categories: Acidification, Eutrophication, Global Warming, and Human Toxicity, cancer. As expected, the electricity mixes with high carbon intensity present high impacts, illustrated by the case of China with an electricity mix based predominantly on coal. In fact, for munitions disposal in China, the environmental impacts are greater than for disposal in Portugal across the majority of the impact categories. The electricity mix in Sweden in 2008 was predominantly hydro and nuclear, leading to lower impacts in all environmental categories.

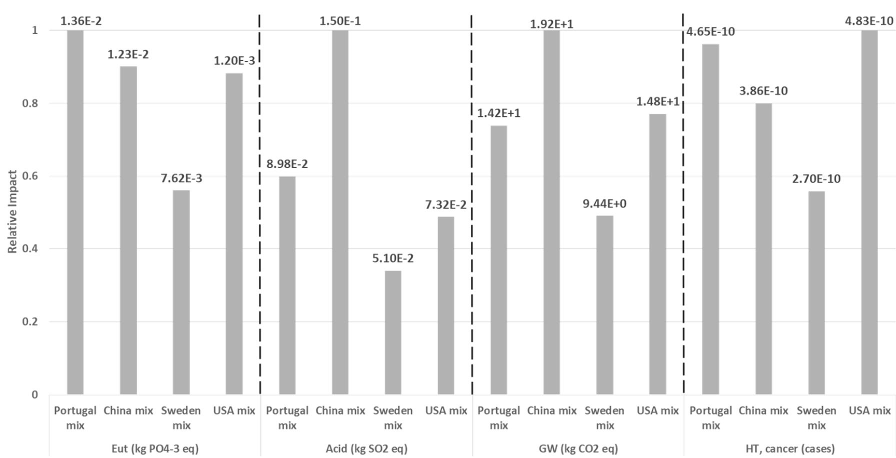

Figure 5. Comparison of impacts associated with the disposal of munitions by incineration in a static kiln considering four different electricity mixes.

These results confirm the benefits from avoiding the impacts from the incineration and gas treatment processes, decreasing the impacts by at least 80%, and also avoiding impacts from production of the emulsion explosive matrix. Even for electricity mixes with low carbon intensity, applying the circular economy approach by down-cycling the energetic material in munitions at end-of-life leads to significant environmental benefits.

4. Conclusions

This work has assessed the potential reductions in primary energy use and environmental and toxicological impacts resulting from adopting a circular economy approach to dispose of energetic material from military ammunition by incorporation into civil explosives. System expansion has been employed to account for the avoided burdens.

Down-cycling of energetic material is an alternative to conventional disposal in which the end-of-life energetic material is incinerated in a static kiln with flue gas treatment. Significant environmental improvements result from avoiding the incineration and flue gas treatment operations which dominate the impacts associated with conventional disposal. Further significant improvements result from reducing the demand for emulsion explosive matrix, thereby avoiding production and transport of the emulsion explosive matrix components. The overall energy, environmental, and toxicological benefits show conclusively that valorization of the energetic material of military munitions by incorporation into civil explosives is an improved environmental solution whatever the background energy system.

Decommissioning military explosives, in part to ensure that they are not available for terrorist activities, is a world-wide problem. However, the approach recommended here may not be viable in countries with relatively small quantities of redundant munitions, so there appears to be a case for an international initiative to pursue this approach. Furthermore, as this work presents the first analysis of the potential benefits associated with the down-cycling of energetic material from ammunition into new products, future analysis can address the potential advantages from recycling other types of energetic material with the employment of different technologies, or explore applying this approach to other products (e.g., boosters).

Even though there are clear environmental benefits to be had from valorizing energetic material at end-of-life, there are still some barriers to incorporating material from military munitions into civil explosives, mainly due to commercial and technical issues. These represent specific examples of more general problems in implementing the circular economy concept [28]. Companies that produce civil explosives would be compelled to inform their clients that they are buying explosives containing recycled material, possibly leading to some variations in their performance and safety characteristics compared with the standard explosives; this may well meet resistance from the producers. Furthermore, the energetic materials to be incorporated into civil explosives would originate from different types of munition, leading to diverse batches with somewhat different specifications. This will require supplementary quality control methods and possibly changes in the procedures for transport and use of some civil explosives.

Author Contributions: C.F. carried out the LCA modelling, with advice from R.C. and F.F. on the use of system expansion and interpretation of the results. J.R. provided expertise on production and management of explosives. All four authors collaborated in drafting the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

To facilitate the detailed analysis of the potential benefits of recycling energetic material in civil explosive production, the environmental life-cycle results were normalized to select the most relevant impact categories. The normalization for the environmental impact categories was carried out using the normalization factors provided by the CML method (referred to the total impact of the EU25+3 economy for the year 2000 [25]). Figure A1 shows the normalized results demonstrating that, Acidification, Eutrophication, and Global Warming are the most significant impact categories.

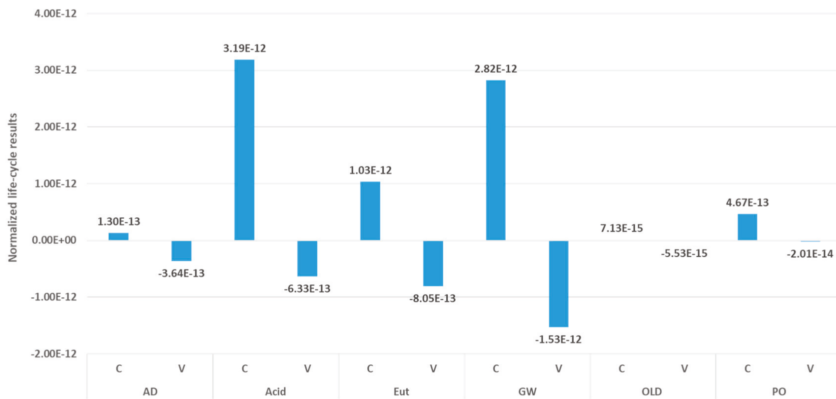

Figure A1. Normalized environmental impacts associated with conventional ammunition disposal by incineration (C), and with down-cycling of energetic material (V) (per kg TNTeq.).

A similar approach was used for normalization of the three toxicological impact categories from the USEtox method, using normalization factors from Benini et al. [29] based on data for emissions in the EU-27 countries for the year 2010. As shown in Figure A2, Human Toxicity with cancer effects emerges as the most significant toxicological impact; the analysis in the results section is therefore presented in terms of the three environmental impact categories noted above and Human Toxicity with cancer effects. It may be noted that the normalization factors for the toxicological effects are associated with much higher uncertainty than those for the other impact categories, as they were calculated using the "recommended" and "interim" impacts. However, the selection of the most significant toxicological impact category, even with a higher uncertainty, will not impact the interpretation of the results.

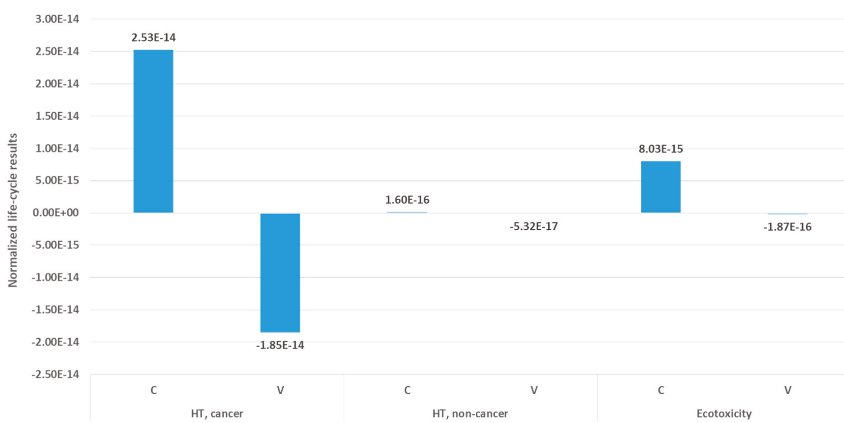

Figure A2. Normalized toxicological impacts associated with conventional ammunition disposal by incineration (C) and with down-cycling of energetic material (V) (per kg TNTeq.).

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Analysis of Evolution Mechanism and Optimal Reward-Penalty Mechanism for Collection Strategies in Reverse Supply Chains: The Case of Waste Mobile Phones in China

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Abstract: The aim of this paper is to discuss the coopetition (cooperative competition) relationship between a manufacturer and a collector in the collection of waste mobile phones (WMPs) and examine the evolution mechanism and the internal reward-penalty mechanism (RPM) for their collection strategies. A coopetition evolutionary game model based on evolutionary game theory was developed to obtain their common and evolutional collection strategies. The pure-strategy Nash equilibriums of this model were obtained which showed their collection strategy choices of perfect competition or cooperation. The mixed strategy Nash equilibrium was obtained which revealed evolution trends and laws. In addition, the optimal RPM was obtained in the sensitivity analysis of related parameters. The example of WMPs in China was taken to examine the simulation of the RPM. Results show that (i) although the manufacturer and the collector may change their strategies of cooperation and competition over time, cooperation is their best choice to increase payoffs; (ii) the optimal RPM is beneficial to propel their cooperation tendency and then to increase their payoffs.

Keywords: reverse supply chain; collection strategy; waste mobile phones; evolutionary game theory; evolution mechanism; reward-penalty mechanism

1. Introduction

Mobile phones have become essential parts of daily life and the most commonly manufactured electronic equipment [1]. Since China became the largest producer and seller of mobile phones in 2004, the total number of mobile phone users has achieved 1.5 billion in 2018 [2]. The life expectancy of a mobile phone is shorter than 3 years according to studies from many scholars [3–5]. Obviously, the generation of waste mobile phones (WMPs) is huge and now they have become an environmental problem as a part of waste electrical and electronic equipment (WEEE). In 2017, there were approximately 1 billion WMPs in China, and the recycling rate was only 2% [6]. However, WEEE management has been implemented in developed countries since 2000 [7–9], and many compulsory laws and directives such as the EU Directive on WEEE (2002/96/EC) [10], its revised version (2008/34/EC) [11], and the newest one (2012/19/EU) [12] have been enacted based on extended producer responsibility (EPR) principles. The Directive (2012/19/EU) requires that 75% of WMPs should be recovered, and 55% of WMPs should be reused and recycled by 2018 [12]. The EPR principles require producers including manufacturers and importers to take responsibility for the whole lifespan of a product, especially for the collecting, dismantling, and recycling at its end-of-life stage [13].

The collection of WMPs in the reverse supply chain (RSC) is mainly conducted by formal collectors in many developed countries. Switzerland first established a formal and comprehensive management system of WEEE, which is well operated with producer responsibility organizations (PROs) [14]. Manufacturers, importers, distributors, and retailers collect WMPs through established collection points and retail locations supported by the Swiss Association for Information, Communication and Organization Technology, which is one of the most important PROs [15]. In Japan, the *Law on the Promotion of Recycling and Reuse of Used Small Electronic Equipment* was enacted to support the tack-back of 28 types of small electronic products including WMPs in 2012 [16]. Under the guidance of related laws, retailers and mobile phone operators have collected WMPs through recycling bins at their business outlets [17].

In many developing countries including China, the collection of WMPs is conducted by formal and informal collectors [18–20]. Street peddlers and repairers in China dismantle WMPs harmfully and crudely and put them into the market with rough refurbishment, who are the leading collectors in the informal collection. As to the formal collection, there are mainly two ways in China. One is the manufacturer's collection, such as the Old-for-New (OFN) service of Mi (http://huanxin.mi.com), and the other is the collector's collection like the third-party collection platform represented by Aihuishou (https://www.aihuishou.com/shouji). They have a competitive and cooperative relationship for WMPs collection. The collector can be served for the manufacturer. On the other hand, they also compete for the surplus value of WMPs such as remanufacturing materials. One of main reasons why they engage in e-waste collection is to recapture the value of the recycled materials and end-of-life products [21]. Their coopetition (cooperative competition) relationship continues throughout the whole game process, and they adjust with each other's strategy according to opponent's responses and their own payoffs.

The relationship between the manufacturer and the collector can be presented by evolutionary game theory (EGT) which assumes the man of bounded rationality [22]. It is more in line with the reality because of incomplete information and changing environment. The EGT emphasizes the behavioral interaction among players which can affect their payoffs directly. The behavioral interaction between the manufacturer and the collector in the WMPs collection is who will do the collection and how to bind them with a contract. They develop their own strategies in the process of the interaction. The EGT can entirely reflect the relationship between strategies change and payoffs fluctuation, can also effectively reflect their complex coopetition relationships. Rosas [23] pointed out that social scientists usually exploit the EGT to study human cooperation. Ji et al. [24] argued that the EGT can effectively observe the changing of cooperation tendency among multi-stakeholders. Some studies have exploited the EGT to analyze the collection of WEEE. Esmaeili et al. [25] adapted the EGT to discuss whether performing collection or not for the manufacturer and the retailer. Wu and Xiong [26] studied cooperation behavior between manufacturers and collectors under a government subsidy mechanism with the EGT.

Except for the subsidy mechanism, the reward-penalty mechanism (RPM) made by the government in a closed-loop supply chain is examined by Wang et al. [27–30]. The RPM is one of incentive mechanisms which are usually used to coordinate forward and reverse supply chains. The producers will face penalties if they cannot achieve the target collection rate set by the EU Directives on WEEE. Unlike this, the Chinese government prefers subsidies or rewards, which set up a WEEE treatment fund in 2012 [31] and added the WMPs to the *Waste Electrical and Electronic Equipment Treatment Directory (2014 Edition)* in 2015 [32]. The EPR principles were adopted in this fund. Specifically, the government levies funds on the electrical and electronic equipment producers and provides subsidies or rewards to authorized WEEE dismantling companies according to their actual disposal quantity. The RPM for the manufacturer and the collector is conducive to enhancing collection rate and increasing their payoffs. In addition, the RPM can be used to promote positive strategy evolution. Therefore, we examine an internal RPM negotiated by the manufacturer and the collector, which is rare in other literature.

Based on the theory and practice of the RSC, EGT, RPM, and the motivating example, we investigate an RSC comprising one manufacturer and one collector under an RPM. This paper uses the evolutionary game to discuss the relationships between members in the RSC and to analyze the evolution mechanism of their collection strategies, meanwhile, an optimal RPM is obtained. Finally, we take the collection of Chinese WMPs as an example to conduct the simulation of the RPM. Specifically, we address the following research questions:

(1) What kind of relationship between the manufacturer and the collector is beneficial to them?
(2) How does the evolution mechanism of their collection strategies affect their coopetition?
(3) What kind of RPM should be negotiated by them?

This paper exploits the EGT to discuss the coopetition relationship between a manufacturer and a collector in the collection and to examine the evolution mechanism and the optimal RPM for their collection strategies. Their strategy changes, evolution trends, and payoff fluctuations have been thoroughly studied, which is rare in other literature. The majority of incentive mechanisms is imposed by the government in a closed-loop supply chain (CLSC); there are few internal RPMs from players. However, this paper provides the internal RPM negotiated by the manufacturer and the collector.

The remainder of this paper is organized as follows. In the next section, we provide a literature review. The coopetition evolutionary game model (CEGM) is given in Section 3. Section 4 provides the analysis of evolutionary stability strategy (ESS) and the detailed analysis of the model including the optimal RPM. The simulation of the RPM is conducted in Section 5. Section 6 concludes this paper, discusses managerial implications, and proposes future research opportunities. List of acronyms in this paper is shown in Appendix A.

2. Literature Review

The RSC contains activities of product acquisition, reverse logistics, testing, sorting, refurbishing, and remarketing [33]. A great deal of work has been done in the WEEE collection, as reviewed in Section 2.1. In Section 2.2, we discuss incentive mechanisms for an RSC. The applications of the EGT are reviewed in Section 2.3.

2.1. WEEE Collection

WEEE management has attracted many scholars' interests all over the world. Hischier et al. [34] investigated the positive impacts on the environment of the Swiss take-back and recycling systems for WEEE. Ylä-Mella et al. [35] described the implementation of the WEEE Directive and the development of the WEEE recovery infrastructure in Finland and found that they have made a success. Chi et al. [4] found that informal collection was the primary disposal channel of urban household e-waste after they investigated the collection channels of e-waste and household recycling behaviors in Taizhou, China. Jang [36] presented an overview of recycling practices and the management of WEEE since the EPR policy was introduced in South Korea in 2003. Pathak et al. [37] pointed out that although the Indian legislation has been improved and the EPR principles have been implemented, the grey market for WEEE has been enlarged by the social-economic structures of India with a large population of lower-to-middle income groups.

WEEE collection is the first and crucial step in an RSC of WEEE. In Europe, the majority of collection schemes for WEEE has been established in partnership with existing municipal collection schemes for recyclables and hazardous household waste, and additional take-back schemes by retailers [38]. In Canada, Recycle My Cell is a national WMPs recycling program which operates more than 3500 drop-off locations in the country. Besides, Customers can return their used mobile devices with a postage-paid service [39]. Similar to Canada, Australia also has over 3500 WMPs drop-off points and provides pre-paid shipping service to return [39]. In Japan, though, consumers must pay the end-of-life fees that cover part of the recycling and transportation costs while manufacturers afford the rest of the cost [40]. Completely different from the above developed countries, the manufacturer, the retailer, and the collector need to buy back WEEE from consumers in China. HUAWEI, one of mobile phone manufacturing giants in China, initiated an online recycling program called "Green Action 2.0" to carry out the OFN policy which provided up to 798 USD cash coupon for new purchase [41]. Large online retailers such as Jingdong and Suning set up OFN websites to collect the WEEE including WMPs. The third-party collection platform represented by Aihuishou also has the online collection system, and it has established four collection modes of store collection, face-to-face collection, mailing collection, and collecting machine collection [42].

There are formal and informal collection channels in many developing countries. Nduneseokwu et al. [43] examined factors influencing consumers' intentions to participate in a formal e-waste collection system in Nigeria, suggested enhancing consumer's intentions to choose the formal collection and developing an e-waste collection infrastructure. Wang et al. [44] investigated barriers to the formal collection of e-waste in China which mainly were households' preference and informal collectors. Chi et al. [4] pointed out that economic benefit and convenience of disposal were the key factors of choosing collection channels for customers in China, and informal collectors had these advantages. Pathak et al. [37] argued that the informal collection and treatment of WEEE in India have become a serious threat to the sustainable development of the country. Li et al. [45] presented governance mechanisms out of governments and enterprises to control informal collection. There are the monopolistic and competitive take-back schemes for WEEE recycling between competing manufacturers and recyclers in Europe. Toyasaki et al. [46] found that the competitive recycling channel usually achieves a win–win situation. In addition to these kinds of collection channels, there are other channels decided by structure power, such as a manufacturer-led collection channel, a retailer-led collection channel, and a third-party collector-led collection channel [47–49].

This paper focuses on the formal collection system of WMPs in China, discusses the coopetition relationship between the manufacturer and the collector and their collection strategies. Different from most of the existing literature, we investigate their parallel relationship in the RSC.

2.2. Incentive Mechanisms for RSCs

Most of incentive mechanisms are set by the government. One of them is government subsidy, several researchers have reviewed the positive effects of subsidies on the WEEE collection especially on the formal one and environment in China [50–52]. In June 2009, the Chinese government introduced the OFN policy which stipulated that consumers trading in WEEE for new goods could get subsidy up to 10% of the price of the new products [53]. Besides, authorized WEEE recycling enterprises can receive subsidies for WEEE treatment provided by the government, which has continued to the present. This policy has greatly promoted the development of the formal WEEE treatment in China. However, this policy towards consumers expired at the end of 2011 for short of financial support. To better implement the EPR principles and maintain the policy sustainability, Gu et al. [54] redesigned the WEEE fund mode in China. Liu et al. [55] agreed that the government subsidy is beneficial to the development of the formal sector, but the marginal effect of that is not strong when at a higher quality level of e-waste. In addition to subsides, the RPM from the government has been examined. Wang et al. investigated some RPMs under the centralized, the manufacturer-led, and the collector-led CLSCs [28]. Wang et al. also examined the CLSC consisting of two sequential competing manufacturers and one retailer with or without the RPM from the government [29].

To the best of our knowledge, few studies discussed incentive mechanisms from members in the RSC, except for Jørgensen et al. [56] and De Giovanni [57], who have examined the endogenous incentive mechanisms, but their setting was the manufacturer as the leader and the retailer as the follower. The most similar setting with this paper is De Giovanni et al. [58], who discussed a two-sided incentive problem in a dynamic CLSC made up of a manufacturer and a retailer to increase the return rate of end-of-use products, and the manufacturer and the retailer carried out the incentive strategies jointly. Different from above literature, our study is focusing on the two-sided internal incentive mechanism negotiated by the manufacturer and the collector and implemented by the manufacturer. The motivation of the mechanism is to coordinate their strategies and to maximize their payoffs.

2.3. Applications of the EGT

The EGT has been used to deal with cooperation and competition relationships between two parties and to observe their evolution trends. Feng et al. [59] applied the EGT to analyze cooperation and competition behavior of partners in the supply chain of prefabricated construction. Cheng et al. [60] discussed the technology-licensing cooperation problem of two firms with the EGT and obtained the evolution trend of the technology-licensing deal and cooperation strategy under the fixed-fee licensing and royalty licensing situation. An evolutionary game model was built by Yuan et al. [61] to analyze the evolution process of long-term cooperation between the manufacturer's emission reduction and the retailer's low-carbon promotion. Ji et al. [24] developed an evolutionary game model to analyze their long-term green purchasing relationships between suppliers and manufacturers and to observe their cooperation tendency. The EGT takes the frequencies of strategies adopted during the evolutionary game process as the evaluation criterion for decision-making. Then the replicator dynamic method [62], the simulation method [63], and the differential equation method [64] were proposed to solve the frequencies and the game equilibrium.

There were many scholars studying the RSCs with EGT. Wang et al. [65] examined whether two manufacturers took an active part in recycling in the RSC with the EGT. Fu et al. [66] studied the recycling channel decision under competition between two RSCs consisting of one recycler and one waste handler respectively based on the evolutionary game. Han and Xue [67] also used the EGT to study the recycling channel decision with two competitive manufactures and one dominant retailer. The EGT was adopted by Tomita and Kusukawa [68] to analyze the evolutionary stability for behavior strategies of the retailer's cooperation and the manufacturer's monitoring in the RSC. In this paper, we also adopt the EGT to examine the collection strategies in the RSC. However, we extend the prior studies to investigate the coopetition relationship between the manufacturer and the collector in the RSC under the RPM, which is one focus of this paper. Their collection strategies and evolution trends, and the optimal RPM are derived by using the replicator dynamics.

3. Coopetition Evolutionary Game Model

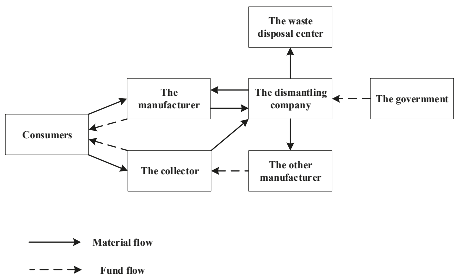
3.1. Problem Definition

The manufacturer such as Mi can collect waste phones by himself and can also authorize the third-party collector such as Aihuishou to undertake the collecting tasks. This paper will refer to the manufacturer as "he" and to the third-party collector as "she" hereinafter. Their choices of strategy are presented in Table 1. When he chooses the competitive strategy, he will undertake the task of self-collection, i.e., take into account both manufacturing and collecting; When he chooses the cooperation strategy, he will authorize her to undertake the collection, but there may be some risks of cooperation such as uncontrollable collecting process and difficult to guarantee service quality. When she chooses the competitive strategy, she will collect his waste phones for other manufacturers, which will reduce his remanufacturing materials; Otherwise, she will collect the waste phones for him.

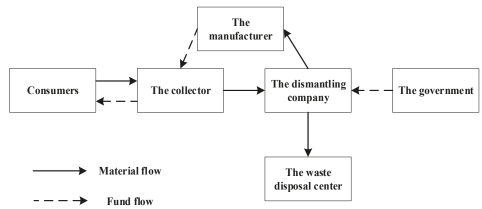
Table 1. Their strategy choices.

	Competitive Strategy	Cooperation Strategy
Manufacturer	Self-collection	Authorizing the collector to undertake collection
Collector	Collecting his waste phones for other manufacturers	Collecting waste phones for him

There are several parties including the manufactures, the collector, the dismantling company, the waste disposal center, the government, and consumers to achieve the collection in the RSC. Consumers' waste phones would be bought back by the manufacturer and the collector for collection, then the waste ones would be disassembled by the dismantling company. The company will deliver remanufacturing materials to the corresponding manufacturer according to the collecting source of the waste phones, namely, returning them to him who takes the self-collection or to the manufacturer who cooperates with her. Here we assume that the other manufacturer does not take the collection. The government funds the dismantling company for environmental protection and resources conservation, and the cooperative manufacturer pays the collector collecting fees. The RSC structure in the competitive and cooperation situation is shown in Figure 1.



(**a**) In the competitive situation



(**b**) In the cooperation situation

Figure 1. RSC structure in the competitive and cooperation situation.

As shown in Figure 1, they compete for the collection of consumers' WMPs in the competitive situation, and she collects his WMPs for the other manufacturer. Then the dismantling company delivers remanufacturing materials to the manufacturers according to the source of the waste. While in the case of cooperation, all the waste ones are collected by her for him. Then the dismantling company only delivers the remanufacturing materials to him. The key point of this RSC structure lies in their choice of collection strategies. Thus, we study the RSC consisting of one manufacturer and one collector.

3.2. Notations and Assumptions

The following notations in Table 2 are used throughout the paper:

Table 2. Notations.

Symbol	Description
Parameters	
v_s	His basic income from manufacturing
e_s	Operating cost of his self-collection including fees of buy-back and transportation
c_s	Risk cost of his choice of cooperation caused by her not achieving the excepted quantity and quality of collected products
v_t	Her basic income from collecting WMPs for other manufacturers
c_t	Initial cost of her choice of cooperation for additional service personnel and facilities
e_t	Operating cost of her collection including fees of buy-back and transportation
l	Reward implemented by him for her successful service
k	Penalty implemented by him for her failed service, which means that she does not meet his requirements for the quantity and quality of the collection
β	Probability of her service failure which depends on the random quantity and quality of WMPs, $0 < \beta < 1$
Δv_s	His potential profit from additional remanufacturing materials in a cooperative strategy
Δv_t	Her potential profit from additional collecting income in a cooperative strategy
Variables	
p	Probability of his choice of cooperation
q	Probability of her choice of cooperation

The following assumptions are made in the light of the actual situation and the characteristics of the model.

(1) The total amount and quality of collected phones would not be changed by their different strategies.

(2) His basic income is greater than the sum of the operating cost of his self-collection and the risk cost of his cooperation, namely, $v_s > e_s + c_s$; Her basic income is greater than the initial cost of her cooperation, that is, $v_t > c_t$.

(3) To ensure that the both sides have the potential to cooperate, their potential profits are higher than cooperative risk inputs, namely, $\Delta v_s > c_s + l$, $\Delta v_t > e_t + c_t + k$.

3.3. Modeling

To improve their cooperative quality and protect their interests, this paper introduced an RPM $(l,\ k)$ under cooperation, which is negotiated by them and implemented by him. Their payoff matrix of the CEGM is set up based on the model descriptions and assumptions above, as shown in Table 3.

Table 3. Payoff matrix of the CEGM.

Manufacturer \ Collector	**Competition (1−q)**	**Cooperation (q)**
Competition (1−p)	$v_s - e_s, v_t$	$v_s - e_s, v_t - c_t$
Cooperation (p)	$v_s - e_s - c_s, v_t$	$v_s - (1-\beta)l + \beta k - c_s + \Delta v_s,$ $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$

As can be seen in Table 3, when they both adopt the competitive strategy, his income is the basic income excluding the operating cost of self-collection, namely $v_s - e_s$, and her income is the basic income v_t; When he takes the competition strategy and she takes the opposite one, his income is still $v_s - e_s$, but her income is the basic income excluding the initial cost of choosing cooperation, i.e., $v_t - c_t$. In addition, when he adopts the cooperation strategy and she is the opposite, his income is the basic income excluding the sum of the operating cost of self-collection and the risk cost of choosing cooperation, i.e., $v_s - e_s - c_s$, and her income is the basic income v_t; When they both adopt the cooperation strategy, his income depends on the RPM, cooperative risk cost, and his potential profit in a cooperative strategy, that is, $v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$, and her income relies on the RPM, her operating cost of collection, her initial cost of cooperation, and her potential profit in a cooperative strategy, i.e., $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$.

If she takes the competitive strategy, his income set (competition, cooperation) is ($v_s - e_s$, $v_s - e_s - c_s$), and he will obviously choose the competitive strategy. However, if she adopts the cooperative strategy, his income set (competition, cooperation) is ($v_s - e_s$, $v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$). Since the latter is bigger, he will choose to cooperate with each other. Similarly, when he chooses the cooperation strategy, she also adopts the cooperation strategy; When he adopts the competition strategy, she adopts the same one. Therefore, the pure strategy Nash equilibriums of the CEGM are (competition, competition), (cooperation, cooperation).

When both of them choose cooperation, their income set (he, she) is ($v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$, $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$), which both reach the maximum value. Besides, the integration of resources caused by cooperation is beneficial to the overall interests of the RSC. Thus, the best choice for them is to adopt cooperative strategies.

In reality, when being under competition, they will vigorously pursue cooperation for greater interests. That is because he needs more remanufacturing materials and she pursues more profits. When they are under cooperation, he would doubt her operation capacity not matched with expenses, and she may dissatisfy their RPM. Therefore, it is not eternally immutable for their cooperative or competitive relationship with each other. In the long run, they will choose a competitive or cooperative strategy randomly.

4. Model Analysis and Discussion

4.1. Analysis of ESS

To obtain the evolution mechanism and the stability state of the coopetition relationship in the RSC, this paper analyzes ESSs.

It can be available from Table 3 that his expected income of cooperative strategy is:

$$E_s^c = (1-q)(v_s - e_s - c_s) + q(v_s - (1-\beta)l + \beta k - c_s + \Delta v_s), \tag{1}$$

and his expected income of competitive strategy is:

$$E_s^m = (1-q)(v_s - e_s) + q(v_s - e_s). \tag{2}$$

Then his average expectation of expected income can be showed as:

$$\overline{E_s} = pE_s^c + (1-p)E_s^m. \tag{3}$$

Similarly, her expected income of cooperative strategy is:

$$E_t^c = (1-p)(v_t - c_t) + p(v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t), \tag{4}$$

her expected income of competitive strategy is:

$$E_t^m = (1-p)v_t + pv_t. \tag{5}$$

Then her average expectation of expected income can be represented as:

$$\overline{E_t} = qE_t^c + (1-q)E_t^m. \tag{6}$$

The replicator dynamics [69] was used to obtain the ESS. The replicator dynamic equation of his cooperative strategy is:

$$\begin{aligned} f(p) = dp/dt &= p(E_s^c - \overline{E_s}) \\ &= p[E_s^c - (pE_s^c + (1-p)E_s^m)] \\ &= p(1-p)(E_s^c - E_s^m) \end{aligned} \tag{7}$$

Put his expected incomes into Equation (7), can obtain:

$$f(p) = p(1-p)[q(e_s - (1-\beta)l + \beta k + \Delta v_s) - c_s]. \tag{8}$$

Similarly, the replicator dynamic equation of her cooperative strategy is:

$$\begin{aligned} f(q) &= dq/dt \\ &= q(1-q)[p((1-\beta)l - e_t - \beta k + \Delta v_t) - c_t] \end{aligned}. \tag{9}$$

When $\begin{cases} f(p) = 0 \\ f(q) = 0 \end{cases}$ is simultaneous, it can obtain $p^* = \frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t}$, $q^* = \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s}$.

In the plane $N = \{(p, q); 0 \le p, q \le 1\}$, there are five equilibrium points including O (0, 0), A (0, 1), B (1, 0), C (1, 1), and M (p^*, q^*). The local stability of the RSC system is analyzed at these five equilibrium points by analyzing the local stability of Jacobian matrix. The partial derivatives of $f(p)$ and $f(q)$ are taken with respect to p and q respectively, and the Jacobian matrix is given as:

$$J = \begin{bmatrix} \frac{\partial f(p)}{\partial p} & \frac{\partial f(p)}{\partial q} \\ \frac{\partial f(q)}{\partial p} & \frac{\partial f(q)}{\partial q} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}, \tag{10}$$

where

$b_{11} = (1-2p)[q(e_s - (1-\beta)l + \beta k + \Delta v_s) - c_s]$, $b_{12} = p(1-p)[(e_s - (1-\beta)l + \beta k + \Delta v_s)]$, $b_{21} = q(1-q)[(1-\beta)l - e_t - \beta k + \Delta v_t)]$, $b_{22} = (1-2q)[p((1-\beta)l - e_t - \beta k + \Delta v_t) - c_t]$.

Denote the determinant of J as det$J$, and $\det J = b_{11}b_{22} - b_{21}b_{12}$. Denote the trace of J as tr$J$, and $\mathrm{tr}J = b_{11} + b_{22}$. According to the method proposed by Friedman [62], the criteria for judging the local stability of the Jacobian matrix are as follows:

The necessary and sufficient condition for the equilibrium point to be an evolutionary stable point is $\det J > 0$, $\text{tr} J < 0$; The necessary and sufficient condition for the equilibrium point to be an instability point is $\det J > 0$, $\text{tr} J > 0$; The necessary and sufficient condition for the equilibrium point to be a saddle point is $\text{tr} J = 0$.

The local stability of the equilibrium points in the RSC system can be obtained by calculation, as shown in Table 4.

Table 4. The local stability of the equilibrium points in the RSC system.

Equilibrium Point	det*J*	tr*J*	Local Stability
O (0, 0)	+	-	Evolutionary stable point
A (0, 1)	+	+	Instability point
B (1, 0)	+	+	Instability point
C (1, 1)	+	-	Evolutionary stable point
M (p^*, q^*)	+	0	Saddle point

In Table 4, "+" represents more than 0, and "-" represents less than 0.

It can be seen from Table 4 that O (0, 0), C (1, 1) are evolutionary stable points; A (0, 1), B (1, 0) are instability points; M (p^*, q^*) is a saddle point. Therefore, the ESSs of this CEGM are (competition, competition), (cooperation, cooperation).

4.2. Coopetition Evolution Analysis

In combination with Tables 3 and 4, point A corresponds to the case where he chooses cooperation and she chooses the opposite one. Her competitive strategy is because she is not satisfied with the RPM. Point B corresponds to the case where he chooses the competitive strategy and she is the opposite. He dissatisfies with her service and adopts a competitive strategy. Their cooperation in these two cases ends in failure. However, they hope to achieve the maximization of their interests by means of cooperation. Therefore, point A and B are instability points.

Point O corresponds to the situation that they both choose competition, and point C corresponds to the cooperation situation. When they do not trust each other, they will be in competition for collection. However, when they reach an agreement, he will be not involved in the collecting business and she will provide quality services for him.

Denote his mixed strategy set as $X_1 = \{[(1-p)s_1, ps_2] | 0 < p < 1\}$, denote her mixed strategy set of as $X_2 = \{[(1-q)s_1, qs_2] | 0 < q < 1\}$, where s_1 represents the pure strategy of competition, s_2 represents that of cooperation. It is easy to verify that $f(p)$ is concave in p and $f(q)$ is concave in q from Equations (8) and (9), resulting in the income of $V(1-p^*, p^*) \geq V(1-p, p)$ and $V(1-q^*, q^*) \geq V(1-q, q)$ for any $0 < p < 1$ and $0 < q < 1$. According to the definition of the mixed strategy Nash equilibrium [70], when he chooses the strategy of $(1-p^*, p^*)$ and she chooses $(1-q^*, q^*)$, they are just the best response to each other, achieving the mixed strategy Nash equilibrium. Thus, (p^*, q^*) is the mixed strategy Nash equilibrium of the CEGM.

In the long-term evolution, they will alternate the situation of competition and cooperation, and achieve a dynamic equilibrium in the saddle point M (p^*, q^*). The evolution laws of the RSC system at different positions of point M are shown in Figure 2.

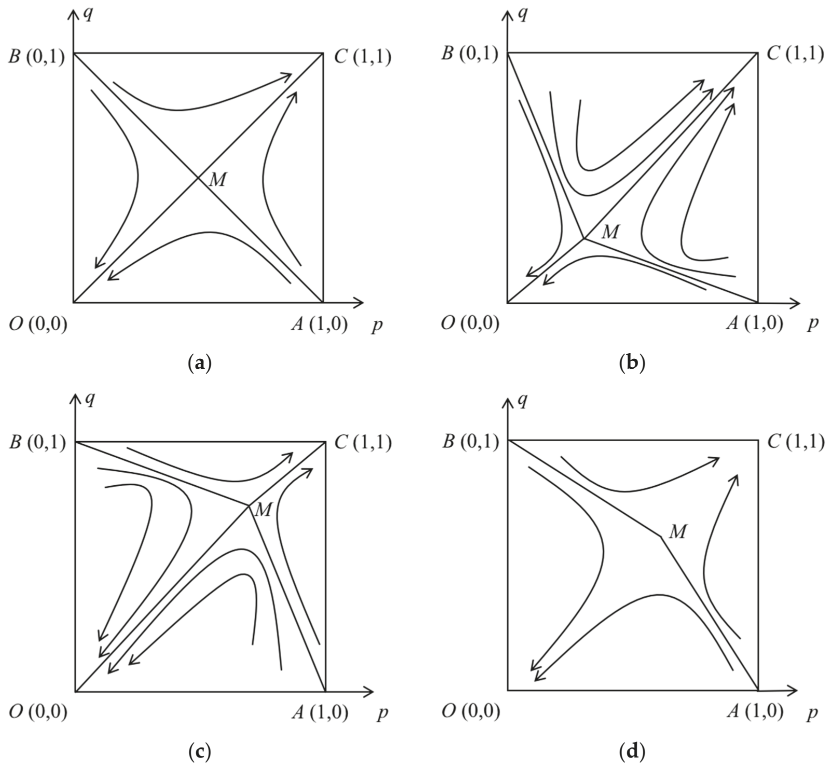


Figure 2. Evolution laws of the RSC system at different positions of point M: (**a**) M is in ($p^* = 0.5$, $q^* = 0.5$). (**b**) M is in ($p^* < 0.5$, $q^* < 0.5$). (**c**) M is in ($p^* > 0.5$, $q^* > 0.5$). (**d**) M is to be determined.

In Figure 2a, the point M is in the position (0.5, 0.5), and they have the same probability of overall competition or cooperation here; The point M is in the position ($p^* < 0.5$, $q^* < 0.5$) in Figure 2b, and they are more convergent to point C (**cooperation**), that is, more likely to choose the comprehensive cooperation strategy; In Figure 2c, it is in the position ($p^* > 0.5$, $q^* > 0.5$), and here they are more convergent to point O (**competition**), namely, more likely to choose overall competition; The position of point M is to be determined in Figure 2d, and it is necessary to determine whether the system converges to point O or point C by means of further analysis.

Denote the area of quadrilateral $AMBO$ as S_1, the area of quadrilateral $AMBC$ as S_2. Then

$$S_1 = \frac{1}{2}(1 \times p^*) + \frac{1}{2}(1 \times q^*) = \frac{1}{2}\left[\frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t} + \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s} \right], \tag{11}$$

$$S_2 = 1 - S_1 = 1 - \frac{1}{2}\left[\frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t} + \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s} \right]. \tag{12}$$

The probability of the system convergence to the equilibrium point O is higher than C when $S_1 > S_2$, as shown in Figure 2c; The probability of the system convergence to O is lower than C when $S_1 < S_2$, as shown in Figure 2b; The probability of the system convergence to O is equal to C when $S_1 = S_2$, as shown in Figure 2a. Therefore, the probability of their competition is positively related to S_1, and the probability of cooperation is positively related to S_2.

It can be seen from Equations (11) and (12) that the factors that influence S_1 and S_2 are Δv_s, Δv_t, c_s, c_t, e_s, e_t, l, k, and β in this game model. The detailed analysis will be presented below.

4.3. Sensitivity Analysis

Combining Equations (11) and (12) and the previous model assumptions, we can get the sensitivity analysis of the related parameters in the CEGM, as illustrated in Table 5.

Table 5. Sensitivity analysis of the related parameters in the CEGM.

	Δv_s	Δv_t	c_s	c_t	e_s	e_t	l	k	β
S_1	−	−	+	+	−	+	$(\mp)^*$	$(\mp)^\sim$	$(\mp)^\#$
S_2	+	+	−	−	+	−	$(\pm)^*$	$(\pm)^\sim$	$(\pm)^\#$
Probability of cooperation	+	+	−	−	+	−	$(\pm)^*$	$(\pm)^\sim$	$(\pm)^\#$

In Table 5, the signs + and − represent an increase and decrease in equilibrium, in response to a marginal increase of the corresponding parameter, respectively. The sign $\pm$ indicates that the equilibrium climbs up and then declines with a marginal increase of the corresponding parameter; The sign $\mp$ indicates that the equilibrium decreases first and then increases with a marginal increase of the corresponding parameter. The superscripts $*$, $\sim$, # denote the different turning points of corresponding parameters.

As shown in Table 5, the bigger Δv_s, the smaller S_1 and the bigger S_2, that is, the probability of the system convergence to O is smaller, but to C is greater. Similarly, the bigger Δv_t, the smaller the probability of the system convergence to O and the greater to C. That means the greater the potential profit, the smaller the barrier to cooperation, and the probability of the waste phone RSC system evolved into cooperation is greater. It implicates that she should increase the collection quantity and quality of WMPs, and he should comply with the contract of cooperation.

The bigger c_s, the bigger S_1 and the smaller S_2, namely, the probability of the system convergence to O is greater, but to C is smaller. Similarly, the bigger c_t, the greater the probability of the system convergence to O and the smaller to C. In other words, the greater the initial cost or risk cost of the cooperation strategy, the lower the willingness to cooperate, and the probability of the system evolved into competition is greater. It shows that she should improve operational management capability to reduce the risk cost of his cooperation strategy. She should also make full use of their resources, for example, take advantage of his sales outlets to conduct collection. He should evaluate her carefully according to her contractual history and operational capability.

The greater the operating cost of his self-collection e_s and the smaller the operating cost of her collection e_t, the greater the willingness to cooperate, and the probability of the system evolved into cooperation is greater. It indicates that she should improve operational management capability to reduce her operating costs.

The greater his reward to her, the greater the probability of her cooperation, but the smaller that of his cooperation. The greater his penalty to her, the smaller the probability of her cooperation, but the greater one of his cooperation. That means there are some contradictions that complicate the effects of the reward implemented by him for her successful service l and the penalty implemented by him for her failed service k on the probability of cooperation. These contradictions implicate that they have an optimal RPM to promote the cooperation tendency. As shown in Table 5, S_1 decreases first and then increases as l or k increases, and S_2 is the opposite, namely, the system first tends to converge to C and then to O. In this case, both l and k have an optimal value, making the probability of the system evolved into cooperation to the maximum. The probability of her service failure β has a direct impact on the implementation of l and k, and its change is consistent with k.

It can be obtained by solving Equation (11) that the optimal reward implemented by him for her successful service l is $\frac{(e_s+\beta k+\Delta v_s)(c_t-\sqrt{c_s c_t})+(e_t+\beta k-\Delta v_t)(\sqrt{c_s c_t}-c_s)}{(1-\beta)(c_t-c_s)}$, and the optimal penalty implemented by him for her failed service k is $\frac{[(1-\beta)l-e_t+\Delta v_t](c_s-\sqrt{c_s c_t})+[e_s-(1-\beta)l+\Delta v_s](c_t-\sqrt{c_s c_t})}{(c_s-c_t)\beta}$. The probability of her service failure that is most conducive to cooperative evolution β is $\frac{(l-e_t+\Delta v_t)(c_s-\sqrt{c_s c_t})+(e_s-l+\Delta v_s)(c_t-\sqrt{c_s c_t})}{(l+k)(c_s-c_t)}$.

In conclusion, the optimal RPM is $l = \frac{(e_s+\beta k+\Delta v_s)(c_t-\sqrt{c_s c_t})+(e_t+\beta k-\Delta v_t)(\sqrt{c_s c_t}-c_s)}{(1-\beta)(c_t-c_s)}$, $k = \frac{[(1-\beta)l-e_t+\Delta v_t](c_s-\sqrt{c_s c_t})+[e_s-(1-\beta)l+\Delta v_s](c_t-\sqrt{c_s c_t})}{(c_s-c_t)\beta}$.

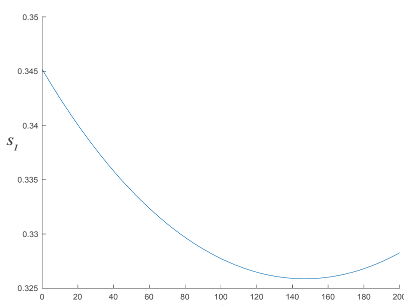
5. Simulation of RPM

Although the theoretical solution of the optimal RPM has been analyzed in Section 4.3, to enhance understanding, a simulation of the RPM is conducted to further clarify the meaning of the optimal RPM. Therefore, we investigated a famous mobile phone manufacturer A and a prosperous third-party collector B as a case study. The parameters, as shown in Table 6, in the following simulation experiments were collected from them, but were modified for the confidentiality reason. These experiments were conducted on the simulation platform of MATLAB R2017b.

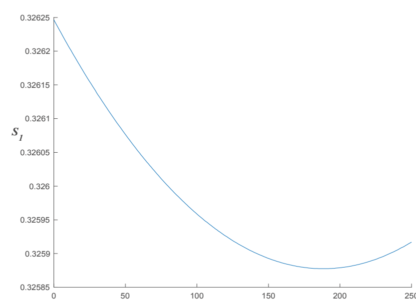
Table 6. The simulation parameters' value.

Parameters	v_s	v_t	c_s	c_t	e_s	e_t	Δv_s	Δv_t	l	k	β
Values	1800	1200	185	180	100	90	580	530	150	160	0.1

To obtain the optimal reward implemented by him for her successful service l, we made the range of l 0–200, and the simulation result is shown in Figure 3a. Similarly, to obtain the optimal penalty implemented by him for her failed service k, we made the range of k 0–250, and the result is shown in Figure 3b.



(**a**)



(**b**)

Figure 3. (**a**) Simulation of S_1 varying with l. (**b**) Simulation of S_1 varying with k.

It can be seen from Figure 3a that S_1 decreases first and then increases as l increases. In this case, when $l = 150$, the value of S_1 is the minimum, that is, it is the largest for the probability of the system evolved into cooperation. k has the similar effect on S_1 as l, which is shown in Figure 3b. When $k = 190$, the value of S_1 is the minimum in this case, namely, it is the largest for the probability of the system evolved into cooperation.

We also made the simulation of S_1 with the ranges of l 0–200 and k 0–250, the result is shown in Figure 4.

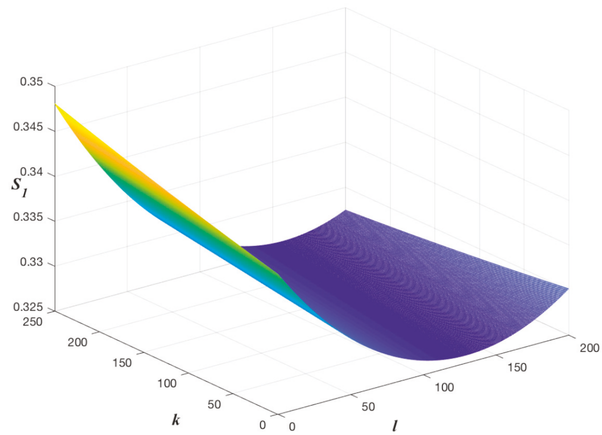


Figure 4. Simulation of S_1 varying with l and k.

It can be seen from Figure 4 that S_1 is under the double influence of l and k. When l is low, S_1 increases with the increase of k, otherwise, S_1 decreases with the increase of k. However, S_1 decreases first and then increases as l increases no matter whether k is big or small. It shows that the optimal RPM consisting of the optimal reward and penalty is interrelated, and they need to be developed at the same time, which is the same as the implication of their formulas. According to the calculated results, the optimal reward and penalty here are 147 and 143, respectively.

6. Conclusions, Insights, and Future Research

This paper presents a CEGM to discuss the coopetition relationship between members in an RSC comprising one manufacturer and one collector and examines the evolution mechanism and the internal RPM for their collection strategies. The pure strategy Nash equilibriums in this model are obtained which show their collection strategy choices of perfect competition or cooperation. However, their cooperative or competitive relationship is not eternally immutable. In the long run, they will choose a competitive or cooperative strategy randomly. The mixed strategy Nash equilibrium and the optimal RPM are obtained in the model analysis and discussion. Finally, this paper takes the example of WMPs in China to examine the simulation of the RPM.

The contributions of this paper include two parts: Firstly, it examines the coopetition relationship between the manufacturer and the collector. It provides common collection strategies and then analyzes the evolution of them, which is of practical significance to implement their collection of WMPs. Secondly, it discusses the two-sided RPM negotiated by the manufacturer and the collector in the RSC, which is beneficial to promote their cooperation tendencies and then to increase their payoffs.

We find that cooperation is the best choice for the manufacturer and the collector to increase their payoffs. There is an optimal RPM for them to propel the cooperation tendency. We provide some practical insights for the manufacturer and the collector as follows. They need to simultaneously negotiate the two-sided RPM consisting of the optimal reward and penalty. The manufacturer should evaluate the potential partner carefully according to her contractual history and operational capability. Once cooperation is reached, he should faithfully perform it. The collector should improve operational management capability to reduce her operating costs and the risk cost of his cooperation strategy and to increase the collection quantity and quality of WMPs. She should also make full use of their resources, for example, take advantage of his sales outlets to conduct collection.

This paper adopts the failure probability of the collector's service instead of the quantitative analysis of her service to define her success or failure. However, the latter is more feasible to implement the RPM, because to obtain the failure probability of her service needs accurate evaluation and prediction. Thus, the future research should quantitatively analyze her service and provide more specific RPM. In addition, other competitors are neglected in this paper, it is more practical to deal with internal and external competition from members in the RSC.

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Appendix A

Table A1. List of acronyms.

Acronym	Explanation
WMPs	Waste mobile phones
RPM	Reward-penalty mechanism
WEEE	Waste electrical and electronic equipment
EPR	Extended producer responsibility
RSC	Reverse supply chain
PROs	Producer responsibility organizations
EGT	Evolutionary game theory
CLSC	Closed-loop supply chain
CEGM	Coopetition evolutionary game model
ESS	Evolutionary stability strategy
OFN	Old-for-New

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Pricing and Collaboration in Last Mile Delivery Services

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Abstract: Recently, last mile delivery has emerged as an essential process that greatly affects the opportunity of obtaining delivery service market share due to the rapid increase in the business-to-consumer (B2C) service market. Express delivery companies are investing to expand the capacity of hub terminals to handle increasing delivery volume. As for securing massive delivery quantity by investment, companies must examine the profitability between increasing delivery quantity and price. This study proposes two strategies for a company's decision making regarding the adjustment of market density and price by developing a pricing and collaboration model based on the delivery time of the last mile process. A last mile delivery time function of market density is first derived from genetic algorithm (GA)-based simulation results of traveling salesman problem regarding the market density. The pricing model develops a procedure to determine the optimal price, maximizing the profit based on last mile delivery time function. In addition, a collaboration model, where a multi-objective integer programming problem is developed, is proposed to sustain long-term survival for small and medium-sized companies. In this paper, sensitivity analysis demonstrates the effect of delivery environment on the optimal price and profit. Also, a numerical example presents four different scenarios of the collaboration model to determine the applicability and efficiency of the model. These two proposed models present managerial insights for express delivery companies.

Keywords: express delivery service; last mile delivery; pricing; collaboration; market share

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1. Introduction

A rapid increase in indirect purchases is accelerating a steep surge of express delivery service market. This incremental result is mainly due to an increasing consumption through online-based transactions such as internet shopping, mobile shopping and TV home shopping, which has naturally led to a growth of express delivery services. Figure 1 shows the recent trend for the courier market in Korea. It is observed that the courier amount has continuously been growing year by year. On the other hand, the unit price has been dropping due to the greater competition among courier service providers [1]. At the end of the day, the express delivery companies with low market share are not likely to survive in competitive market and cannot help avoiding collaboration for increasing their market shares company. More than 80% of market is occupied by only five companies and especially, about 67% is by three companies and a big on covers 45% of entire market [1].

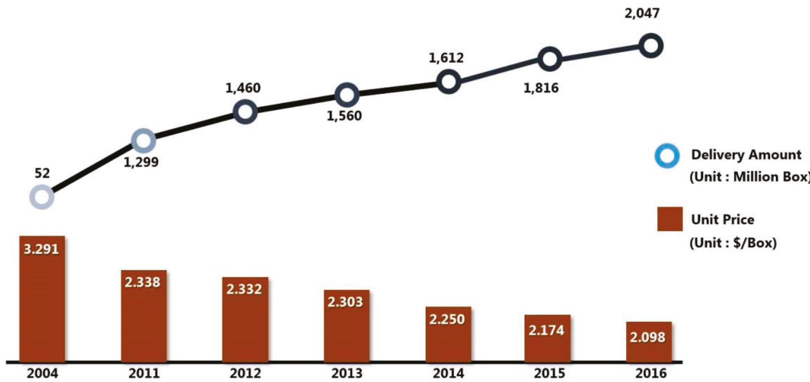

Figure 1. Trend for express service market in Korea [1].

Based on a recent article by Business Insider their shares of delivery costs are reported to be 4%, 37%, 6% and 53%, respectively [2].

Many researches related to the express delivery companies focused on cost minimization by varying network distances. Therefore, since the transport networks managed by express delivery companies already reflect delivery environment, it can be said that express delivery companies are using the optimal route. In addition, hub location problem, which is dealt with express delivery related researches, is also reflected well in the real world. Thus, cost reduction through relocation of the hub terminal is not easy since express delivery companies' hub terminals are already located in near optimal locations. Therefore, profit maximization through cost reduction from other processes is needed instead of cost minimization through changing already existing networks.

As delivery supply is increasing immensely every year, the express delivery companies are planning enormous investments in expansion of hub terminals to handle increased delivery amount. However, as expanded hub terminals deal with increased supply, securing massive delivery quantity raises another problem. In order to obtain increasing delivery quantity, price reduction can be one solution, but there needs to be a fundamental solution if the investment is on large scale to secure delivery supply that will guarantee the company's profitability.

This study emphasizes delivery amounts as market density in perspective of delivery service company and proposes a pricing model to confirm profitability in consideration of the market density. Also the variation of maximum profit in regards of price changes through the analysis of the pricing model is suggested. In addition, this paper suggests the collaboration model as a solution to increase competitiveness and to secure delivery quantity to small and medium-sized companies, to whom massive investment is difficult. This model is a strategy for small and medium-sized companies to win competitiveness against major companies. Also through collaboration, participating companies can reduce cost and increase profit through collaboration and decrease the CO_2 emission quantity generated through transportation simultaneously. With respect to these two solutions, we suggest managerial insight on market density and pricing with sensitivity analysis and numerical example.

The rest of the paper consists of the following: Section 2 introduces the previous studies related to pricing and collaboration of express delivery companies. Section 3 describes the definition of pricing and collaboration of express delivery companies. Section 4 demonstrates two types of mathematical models. Section 5 shows two numerical examples. Section 6 suggests managerial insights gained by analyzing the results from Section 5. Lastly, Section 7 provides the conclusion and further research prospects.

2. Literature Review

2.1. Last Mile Delivery

While many analytical studies related to express delivery services have been undertaken, the literature dealing with the market density and price decision in the last mile delivery services is scarce. Boyer et al. evaluated the effects of customer density and delivery window patterns in the last mile delivery process [3]. They performed a simulation where customer density and delivery window length were considered as variables and analyzed the effect on the last mile route efficiency. Gevaers et al. developed a last mile typology and instrument to simulate the total last mile costs. The transportation cost was derived through considering the transportation time and distance [4]. Kim et al. analyzed the impact of increasing demand on the parcel distribution network structure in terms of minimizing transportation and sortation costs [5]. Alibeyg et al. developed the net profit model that maximizes profit due to the routing commodities, which mainly focused on network design to maximize the net profit [6]. Zhou et al. suggested a location-routing problem with simultaneous home delivery and customer pickup [7]. Hu et al. proposed a vehicle routing problem with hard time windows under demand and travel time uncertainty [8]. The object of the model is to minimize the number of vehicle routes and total travel distance. Xuefeng et al. suggested a multi-objective location-routing problem with simultaneous pick-up and delivery [9]. Zhou et al. proposed a bi-level multi-sized terminal location-routing problem with simultaneous home delivery and customer pickup [10]. Regarding market density or demand for delivery services, Felisberto et al. introduced recipient pricing in the postal sector and tested with Swiss post data by considering the area and the amount of congestion [11]. Cebecauer et al. used Open Street Map data to model the demand points which approximate the geographical location of customers, and the road network, which is used to access or distribute services. They considered all inhabitants as customers, using population grids, and compared two different demand models by estimating the optimal structure of a public service system due to the differences between population grids [12].

2.2. Pricing Decision

Numerous studies have been undertaken in various industry fields related to the price-demand model. Mills introduced a single-period newsboy model with a linear demand function [13]. Polatoglu considered simultaneous pricing and procurement decisions associated with a single-period pure inventory model under deterministic or probabilistic demand [14]. Abad investigated a dynamic pricing and lot-sizing problem with a more general demand function [15]. Hong and Lee proposed model that the price and guaranteed lead time decision of a supplier offering guaranteed lead time for product including a lateness penalty [16]. The expected demand is suggested in a function of the price, guaranteed lead time and lateness penalty. Hong and Lee also proposed an optimal time-based consolidation policy with price sensitive demand [17]. They considered a single-item inventory system where shipments are consolidated to reduce the transportation and developed a mathematical model to obtain the optimal price, replenishment quantity and dispatch cycle to maximize the total profit. Ahmadi-Javid et al. considered a profit-maximization location-routing problem with price-sensitive demands [18]. The problem determined the location of facilities, the allocation of vehicles and customers to established facilities and the pricing and routing decisions in order to maximize the total profit.

2.3. Collaboration

Related research on collaboration have been studied in various industry fields have been studied. Cruijssen et al. measured the dependence of the synergy on a number of characteristics of the distribution problem under consideration and found that significant cost savings are achieved [19]. Lozano et al. suggested a linear model to study the cost savings through forming the transportation [20]. They solved an optimization model for different collaboration scenarios. Kimms and Kozeletskyi suggested a cost allocation scheme for a horizontal cooperation among traveling salesmen providing expected costs for the coalition members [21]. They calculated cost allocation by using the core concept. Wang et al. suggested a collaborative multiple centers vehicle routing problem with simultaneous delivery and pickup to minimize operating cost and the total number of vehicles in the network [22]. They proposed a hybrid heuristic algorithm combining k-means and non-dominating sorting genetic algorithm (GA). Cheung et al. proposed an integer programming model for collaborative service network design by sharing service centers [23]. Ferdinand et al. suggested a collaboration model considering pick-up and routing problem of line-haul vehicles for maximizing the profits of participating companies [24].

In this paper, the travel time was computed through considering market density in unit delivery area and developed the function of last mile delivery time regarding market density (LMF) by solving the travelling salesman problem (TSP) by using GA. Most of the studies dealing with price and cost in last mile delivery and express delivery considered minimizing the cost through optimizing the network design. They also converted transportation time into cost with coefficient values. Instead, we suggest LMF converts market density into demand and computes travel time. The relationship between delivery service and market density was studied before by [3], however, they only performed a simulation experiment and did not suggest any models. We propose LMF and the pricing model which considered market density and travel time simultaneously. The profitability in last mile delivery is computed in the pricing model by considering the changes in the market density and travel time. The pricing model decides the optimal price to maximize the profit which was used in various industries for a long time. As our study focuses on the price decision in last mile delivery, we calculate the travel time by considering the market density and converting it into a linear demand function [15]. By applying the LMF into the pricing model, more realistic-pricing model for the last mile delivery process was proposed, and observed the effect of the market density in the travel cost, optimal price and profit from last mile delivery. In addition we propose the collaboration model for last mile delivery companies. Participating companies share terminals in separate delivery regions and consider which terminal to share. The incremental profit is calculated. The total profit from collaboration is computed by using max–min criteria.

3. Problem Statement

In the era of time-based competition, today's customers begin to demand responsiveness as an integral part of a service. As consumers increasingly turn to e-commerce for all their shopping needs, a quick response service becomes a critical mission for logistic companies and retail partners across the world. Express delivery companies have made several types of efforts for speedy fulfilment, most of which are focused on a delivery service network, terminal productivity and vehicle routing and scheduling, etc. Recently, last mile delivery as the final step of the delivery process, has emerged as a hot issue in fast delivery. As described earlier by Business Insider, the share of last mile is 53%, the highest of the elements of delivery cost [2]. In addition, last mile can be a key to customer satisfaction since it becomes the contact point at which the parcel finally arrives at the buyer's door.

The objective of this study is to emphasize the impact of market density on price decision and forming the strategic alliance. First, we propose the delivery time-market density model. Secondly based on the time-market density model, two kinds of strategies to survive in the express delivery market are suggested; adjusting the price to maximize the profit, and reducing the transportation cost by forming a collaboration. In general, an express delivery service network consists of customer, service centers and consolidation terminals. Customers can be classified into three sub-regions: residential; industrial; commercial areas, where customers either ship or receive ordered parcel items. The service centers are used as a transshipment and temporary storage facility connecting customers to a consolidation terminal. At the consolidation terminal, customer orders are consolidated into larger shipments, mixed and then loaded onto delivery trucks for local deliveries [25]. This study mainly focuses on the last mile of the final step of the shipment process, which is depicted in Figure 2.

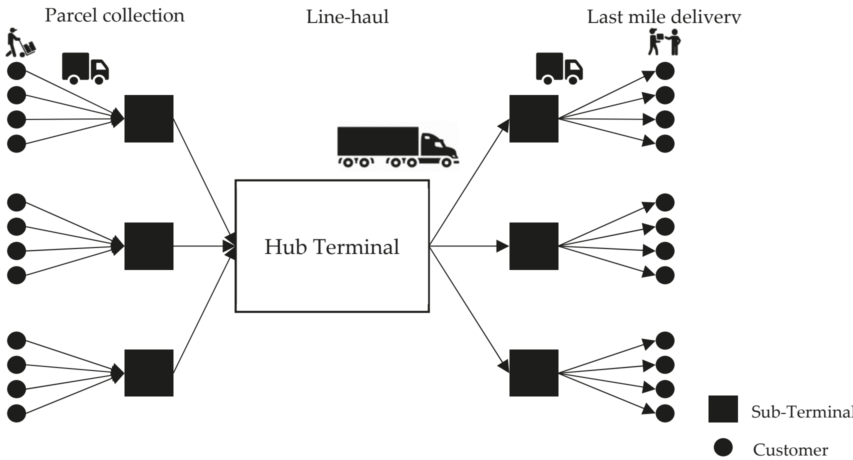

Figure 2. An example of express delivery service flow.

This study is divided into three sub-problems: First, an approximate function of last mile delivery time regarding market density (LMF) is derived using GA-based simulation results of traveling salesman problem with randomly generated customers. Next, according to LMF, a procedure is carried out for searching an optimal price for maximizing profit. Lastly, a collaborative delivery system is suggested for extending market share. For these purpose we make the following underlying assumptions throughout the paper:

(1) Annual delivery service demand is evenly distributed and depends on the delivery service price.
(2) Market share of each express delivery service company is the same in all service areas regardless of regional characteristics, which affects last mile delivery time.
(3) Moving truck/worker and transaction to recipient, transaction time is ignored.
(4) Although delivery costs comprise collection, sorting, line-haul and last mile costs, other costs excluding last mile cost are constant regardless of service price.
(5) Most last mile delivery services are operated in one shift per day. However, delivery services in some companies are performed in two or three shifts in a day.
(6) Daily working time for each express delivery company is the same.

4. Model Design

This section describes two methodologies to increase competitiveness of delivery companies; the first one is to increase their profit by controlling delivery service price and the second one is to introduce a collaborative delivery system for occupying stable market share. Prior to developing the system methodologies, a change of last mile delivery time related to market share is investigated.

4.1. Last Mile Delivery Time Function with Respect to Market Density

In order to observe a trend of last mile delivery time related to market share, actual delivery data was collected from three regions of a Korean express delivery company, which are shown in Figure 3. The company operates three shifts in a day and has around 40% market share in express delivery service market in Korea. It can be observed that the last mile delivery time depends on the attributes of service areas. If we can derive a relation equation of last mile delivery time versus market density, last mile delivery time for each service region can be found under the assumption that market share and attributes of regions are given.

For this purpose, a simulation for gathering last mile delivery data according to density has been carried out. The data is obtained by solving the TSP. The procedure for deriving a last mile delivery function of market density is described as follows:

(Step 1) Generate random demand points within unit square. At this time, we assume that the market density is 10% if 10 demand points are generated.
(Step 2) Solve TSP by a GA-based heuristic assuming that the position of service center is located at (0, 0) and then calculate the average moving time. For every market density, 100 experiments are done.
(Step 3) By continuously increasing demand points by 10 up to 100(%) demand points, the average traveling time is calculated. It is performed under the assumption that all generated demand can be served by only a truck.
(Step 4) If we denote market density as an independent variable, we can find an approximate LMF.
(Step 5) Define a time shape as an average last mile delivery time to a LMF value with the same market share. Then we can estimate a trend of last mile delivery time according to the change of market share.

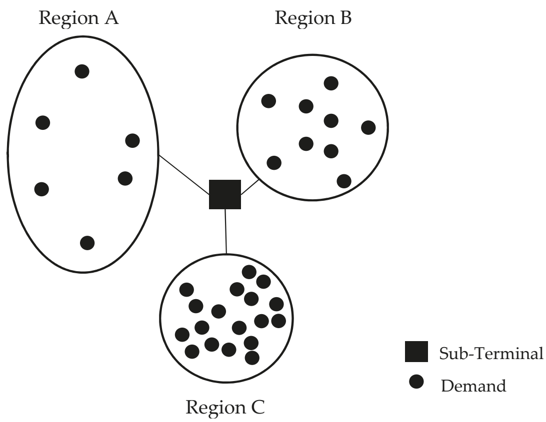

Figure 3. Last mile delivery time pattern in service region during a shift.

With average delivery time related to market density from the results of the GA heuristic in Table 1, the LMF, depicted in Figure 4, can be expressed as:

$$f(\pi) = 0.00005\pi^2 - 0.8347\pi + 0.3764 \quad (1)$$

where π denotes market density and a coefficient of determination, R^2 is 0.9896.

If data collection and analysis for some service regions is performed, we can calculate the time shapes for the service regions, which enables us to estimate the trend in unit last mile delivery time according to market share.

Table 1. Average last mile delivery time from the genetic algorithm (GA) results.

Market Density	**0.1**	**0.2**	**0.3**	**0.5**	**0.7**
Delivery time per box	0.3129	0.2137	0.1583	0.0859	0.0331

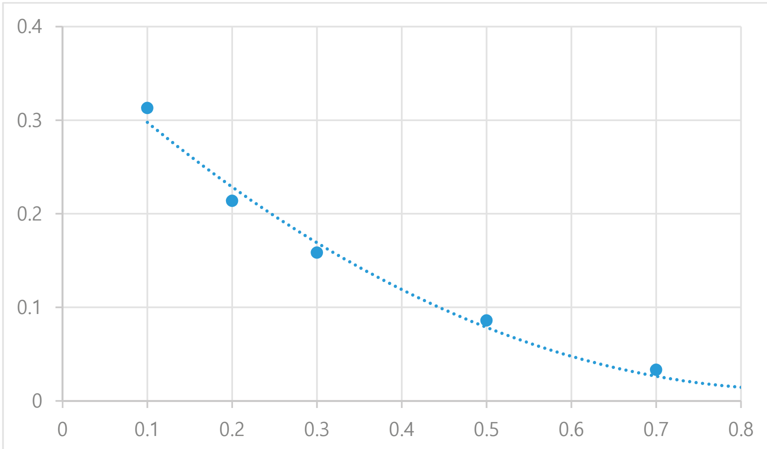

Figure 4. An example of last mile delivery time function of market density.

4.2. Pricing Model

In this section, the pricing model for an express delivery service considering the average last mile delivery time according to market share of the company is developed. The objective of the model is to maximize the profit of express delivery company by adjusting the unit delivery price. Reducing the price can expand market share and increase possible customer density, which can provide unit delivery cost, especially last mile delivery cost. Prior to developing the profit model, the following notations are introduced.

Notations for Pricing Model

p	Unit delivery price
c	Unit last mile delivery cost
$D(p)$	Delivery demand function, which is defined as $a - bp$, where $a > 0$ and $b > 0$
N	Total delivery demand in certain region
t	Average last mile delivery time per delivery service
T	Daily working time
d	Daily delivery amount
w	Daily cost for last mile delivery worker, i.e., daily worker income
K	Other delivery cost excluding last mile delivery cost

Model Design

In order to establish the profit model, unit last mile delivery cost is firstly derived with the relationship between daily delivery amount and last mile delivery time per delivery service. The daily delivery amount during working time can be represented as:

$$d = \frac{T}{t} \tag{2}$$

with daily delivery amount, daily delivery worker cost becomes:

$$w = c \times d \tag{3}$$

Assuming that w is constant regardless of service areas, unit last mile delivery cost, c is obtained by:

$$c = \frac{w}{d} = w \times \frac{t}{T} \tag{4}$$

This means that last mile delivery cost for each service region depends on average last mile delivery time, which is expressed as a function of market density. From now on, market share is derived with unit delivery price. If total delivery demand, N and the demand for a company in any region, $D(p)$ are given, the density for the company is defined as $\frac{D(p)}{N}$. According to Abad et al.'s linear demand function [15], the demand function in this paper is referred as a linear demand rate function of price, $D(p) = a - bp$, where $a > 0$ and $b > 0$. With $D(p)$ and (1), unit last mile delivery cost, c can be represented as a function of unit delivery price, $c(p)$, which is:

$$c(p) = w \times \frac{(0.00005)\left(\frac{a-bp}{N}\right)^2 - 0.8347\left(\frac{a-bp}{N}\right) + 0.3764}{T} \quad (5)$$

Therefore, the pricing model is defined as:

$$\text{Max } Z(p) = (p - c(p))D(p) - K \quad (6)$$

$$\text{where } 0 < p < \frac{a}{b} \quad (7)$$

In the objective Function (6) K means other delivery service cost excluding last mile delivery cost such as collection, terminal operating and line-haul costs, etc. and is assumed to be independent of p. Since $Z(p)$ is a polynomial function of p, we can find an optimal solution considering the constraint (7). The optimal price for profit maximization is found in the pricing model. In order to obtain an optimal solution, we evaluate the optimal price to maximize the profit through differentiation. Since the objective function is a cubic function, we obtain two different optimal prices. Also, since the delivery demand follows a function of $D(p) = a - bp$, the delivery demand needs to be larger than 0. Thus, the optimal price should be within the range of $0 < p < \frac{a}{b}$. We seek the existing optimal price within the corresponding range and derive maximum profit relative to the optimal price. The calculation of the optimal price and profit is explained precisely in the Appendix A.

4.3. Collaboration Model

In this section, the collaboration model for express delivery service to expand market share of the company is proposed. While the pricing model is recommended for most companies regardless of their market shares, the collaboration model is mainly applied to small and medium-sized delivery companies.

A mathematical model for collaborative last mile delivery is developed to maximize the incremental profit of each participating express delivery company by saving last mile delivery cost. Suppose there is a county with n service regions, which are served with m express delivery companies. Each company has a relatively small delivery amount, which incurs a higher last mile delivery cost compared to the companies with lager market share. Collaborative delivery is proposed to expand their service density, and ultimately to decrease last mile deliver cost. The collaboration implements as follows:

(a) In most service regions, only a single company can do a last mile delivery service.
(b) The delivery amounts of the other companies are all assigned to the selected company after collaboration.

The following notations are introduced to establish a multi-objective integer programming model for collaborative last mile delivery:

Notations for Collaboration Model

I	Set of express delivery companies, I = {1,2, . . . ,m}
J	Set of service regions in which service centers are to be merged, J = {1,2, . . . ,n}
c_{ij}	Unit delivery cost of company i in the service region j, $i \in I$, $j \in J$
t_{ij}	Unit delivery time of company i in service region j, $i \rightarrow \in I$, $j \in J$
d_{ij}	Daily delivery amount of company i within the merging region j, $i \in I$, $j \in J$
D_j	Total delivery amount of collaborating companies in service region j, $j \in J$
c_j^1	Unit delivery cost after alliance in the service region j, $i \in I$, $j \in J$
c_j^2	Unit mandated delivery cost after alliance in the service region j, $i \in I$, $j \in J$
ts_j	Time shape of service region j representing regional attribute, $j \in J$
x_{ij}	Binary variable such that x_{ij} = 1, if company i is responsible for service region j after alliance, x_{ij} = 0 otherwise, $i \in I$, $j \in J$
L_i	Lower bound for number of service regions of company
U_i	Upper bound for number of service regions

Model Formulation

Since last mile delivery time of company i for a service region j is obtained by multiplying time shape ts_j and the value from (1), therefore, we can derive last mile delivery cost, c_{ij} for each company from (1) and (4).

After applying a collaborative last mile delivery service, the incremental profit of company i through an alliance can be divided into three portions. First, if company i is responsible for service region j, the incremental profit for its own demand becomes $(c_{ij} - c_j^1)d_{ij}x_{ij}$. In addition, the company can get the profit, $(c_j^2 - c_j^1) \times (D_j x_{ij} - d_{ij})$ for the demands of the other companies. On the other hand, even if company i does not have a right to do a delivery service in the service region j, its incremental profit for its own demand is $(c_{ij} - c_j^2) \times d_{ij}(1 - x_{ij})$. Then by summing the three portions of incremental profits of company i, the objective function for company i can be derived as follows (8):

$$\text{Max} \quad g_i(x) = \sum_j [(c_j^2 - c_j^1)(D_j + d_{ij})x_{ij} + \{c_{ij} + c_j^1 - 2c_j^2\}d_{ij}] \tag{8}$$

Therefore, the collaboration model can be formulated as multi-objective integer programming model with m objective functions:

$$\begin{aligned} \text{Max} \quad g_1(x) &= \sum_j [(c_j^2 - c_j^1)(D_j + d_{1j})x_{1j} + \{c_{1j} + c_j^1 - 2c_j^2\}d_{1j}] \\ &\vdots \\ \text{Max} \quad g_m(x) &= \sum_j [(c_j^2 - c_j^1)(D_j + d_{mj})x_{mj} + \left\{c_{mj} + c_j^1 - 2c_j^2\right\}d_{mj}] \end{aligned} \tag{9}$$

Subject to,

$$\sum_{i \in I} x_{ij} = 1, \qquad j \in J \tag{10}$$

$$L_i \leq \sum_{j \in J} x_{ij} \leq U_i, \qquad i \in I \tag{11}$$

$$x_{ij} \in \{0, 1\}, \qquad i \in I,\ j \in J \tag{12}$$

The objective Function (9) represents the sum of incremental profit obtained through collaboration. Constraint (10) assures that only one service center can be selected for the last mile delivery service in each service region. Constraint (11) implies that the number of service regions should belong to the controlled range. Finally, Constraint (12) represents a binary variable as decision variables showing which company is responsible for each service region. Since in the mathematical model there are

m objective functions representing the net profit increases of m companies, there exists a trade-off relationship with each other.

The proposed collaboration model is a multi-objective assignment problem where the objective is to maximize the incremental profit by forming a collaboration. Under the assumption that only one terminal is used in one region, we calculated reduced cost and incremental profit for participating companies by using max–min criteria. Also, we evaluated the determination of which company's terminal in the region will be used.

The maximum profit of the objective function is derived in usage of max–min criteria. This collaboration methodology is used to reduce the rate of imbalance rate of distribution of the total profit from collaboration to compromise the optimal solution in the win–win situation of each company.

5. Numerical Example

Two illustrative examples are provided to explain the appropriateness of the pricing and collaboration model. We performed sensitivity analysis for the pricing model considering parameter values in the model. Also, we calculated incremental profit by using collaboration model in 4 different scenarios

5.1. Pricing Model

The following parameters are used in the first case. $a = 200$, $b = 30, K = 1$ and $N = 800$. We assume that daily total working hours are $T \in [9, 10, 11]$. We examined how difference in labor cost and working time affects optimal price and profit.

From Table 2 and Figure 5, the optimal price increases as the labor cost increases. As for an express company, when the labor cost increases, it has to increase the price in order to secure the least profit. When daily working time is short, the optimal price increase.

Table 2. The optimal price and the profit with w for different values of T ($N = 800$).

w	Optimal Price			Profit		
	$T = 9$	$T = 10$	$T = 11$	$T = 9$	$T = 10$	$T = 11$
150	6.2555	5.70465	5.32854	1.425887	13.72849	29.78912
155	6.466826	5.858183	5.447527	−0.44777	9.095547	23.92256
160	6.694724	6.021343	5.572731	-	5.236412	18.55562
165	6.941222	6.195066	5.70465	-	2.226224	13.72849
170	7.208695	6.38041	5.843841	-	0.150178	9.485806
175	7.499937	6.578584	5.990921	-	−0.89474	5.877254
180	7.818266	6.790967	6.146581	-	-	2.958326
185	8.167645	7.019143	6.311595	-	-	0.791176
190	8.552851	7.264943	6.486831	-	-	−0.55434
195	8.979691	7.530491	6.67327	-	-	−0.99942

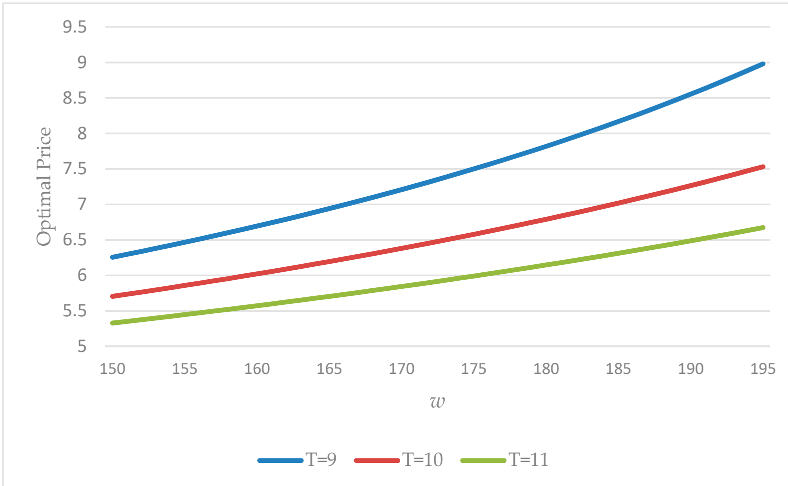

Figure 5. Variation of the optimal price with w for different values of T (N = 800).

Figure 6 shows the variation of the profit when labor cost and daily working time differ. When labor cost increases, the profit decreases. A company can see the certain point where the profit may not occur from the delivery when labor cost reaches a certain point. Difference in daily working time affects the decreasing rate of profit as labor cost increases. This shows that a company cannot increase labor cost infinitely, and it can calculate the standard for the labor cost.

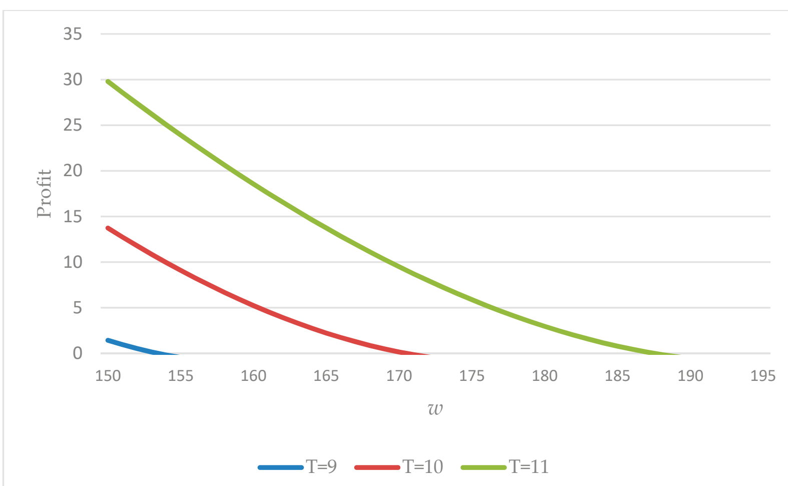

Figure 6. Variation of the profit with w for different values of T (N = 800).

We then performed another case where a = 200, b = 30, K = 1 and w = 150. We assume that daily total working hours are $T \in [9,10,11]$. Table 3 explains the difference in optimal price and profit when total delivery demand in certain delivery region changes.

Table 3. The optimal price and the profit with N for different values of T (w = 150).

N	Optimal Price			Profit		
	T = 9	T = 10	T = 11	T = 9	T = 10	T = 11
800	6.2555	5.70465	5.32854	1.425887	13.72849	29.78912
850	6.280289	5.752257	5.384697	1.279631	12.99963	28.49699
900	6.299942	5.790785	5.430799	1.163678	12.40976	27.4362
950	6.315905	5.822606	5.469326	1.069494	11.92258	26.54974
1000	6.329129	5.84933	5.502002	0.991475	11.51343	25.79788
1050	6.340262	5.872092	5.530067	0.925788	11.16495	25.15214
1100	6.349765	5.891711	5.554432	0.869723	10.86457	24.59153
1150	6.35797	5.908797	5.575783	0.82131	10.60299	24.10025
1200	6.365127	5.92381	5.594647	0.779083	10.37313	23.6662

Figure 7 shows the difference in rate of optimal price when total delivery demand changes. The increase in total delivery demand in a region is equal to the decrease in the market density. Therefore, the price increases when the market density decreases. The effect of the total working time to the optimal price showed similar results as the first case. When total working time increases, the optimal price increases.

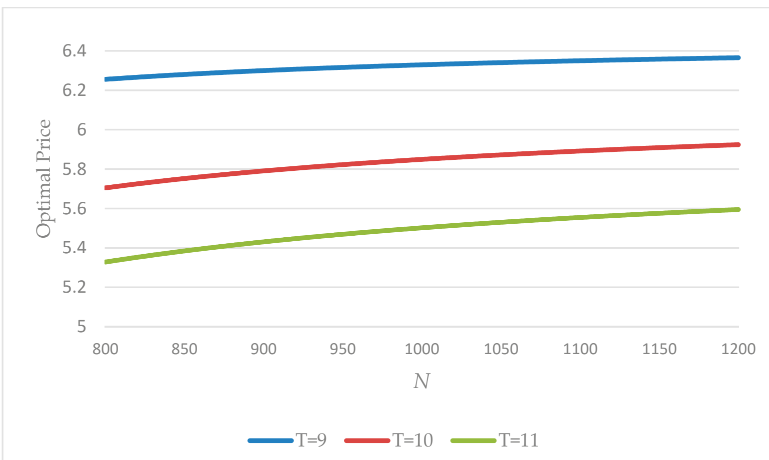

Figure 7. Variation of the optimal price with N for different values of T (w = 150).

Figure 8 shows the variation of the profit when total delivery demand changes. Increased total delivery demand results in the reduction of market density, and directly affects the profit. The effect of the difference in the total working time showed similar results as in the first case. In the second case, when demand parameter is a = 300 and b = 30, the total working time must exceed 9 h per day because, as shown in Figure 8, the profit does not occur from the delivery.

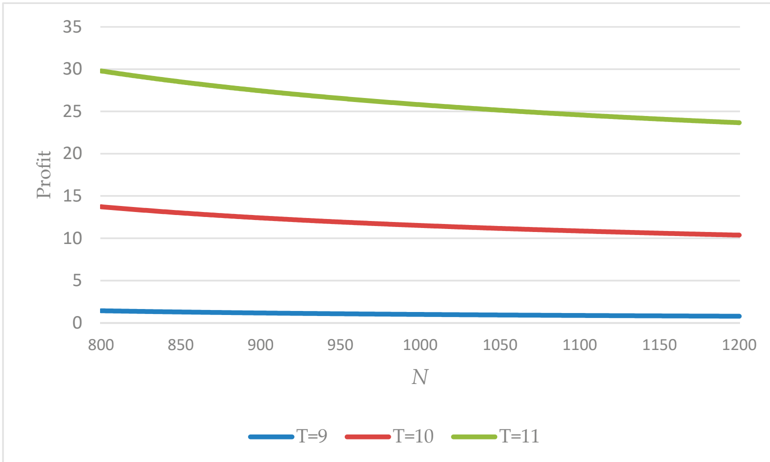

Figure 8. Variation of the profit with N for different values of T (w = 150).

5.2. Collaboration Model

We assumed that there are three express service companies, and we calculated the incremental profit from four different collaboration scenarios where the market density for each company differs: (1) 5%, 10% and 15%, (2) 5%, 5% and 20%, (3) 9%, 10% and 11%, (4) 5%, 12% and 13%. An area is selected for a collaborative last mile delivery service with express service companies. The area is divided into 10 service regions according to regional attributes, which are shown with the demand of each company in Tables 4–6. The tables respectively show last mile delivery time and unit last mile delivery cost for each company according to the regional attributes. Time shape values for each region are obtained by using the last mile delivery time function of market density and actual average delivery time. Assuming that each delivery service worker's income is constant regardless of the number of units, the delivery costs are calculated. We also assumed that daily working hours are eight hours, and transaction time per delivery order is two minutes. C1 and C2, shown in the last two columns in Table 6, represent the delivery cost after collaboration and mandated delivery costs. In the first case, by considering current market shares of each company, the lower bound and upper bound of selected service regions are defined as 1 and 3 for company A, 3 and 5 for company B, and 5 and 7 for company C. Applying Chung et al.'s procedure to the collaboration model with Tables 4–6, we can obtain the optimal solution based on max-min criterion using Excel Solver, which is shown in Table 7. We applied the same procedure for the rest of the scenarios and compared the results [23].

Table 4. Data for companies A, B, and C.

Service Region	Last Mile Delivery Demand Amount		
	A	B	C
1	45	90	135
2	43	86	128
3	42	83	125
4	41	82	123
5	40	79	119
6	37	75	112
7	36	72	108
8	35	70	105
9	34	67	101
10	33	66	99

Table 5. Last mile delivery time according to regional attribute.

Service Region	Time Shape	Market Density				
		0.05	0.1	0.15	0.25	0.3
1	14.4	4.84	4.30	3.79	2.88	2.48
2	17.3	5.81	5.16	4.55	3.46	2.98
3	19.2	6.46	5.73	5.06	3.85	3.31
4	20.2	6.78	6.02	5.31	4.04	3.48
5	22.1	7.43	6.59	5.81	4.42	3.81
6	25.9	8.72	7.74	6.83	5.19	4.47
7	28.8	9.69	8.60	7.58	5.77	4.97
8	30.7	10.33	9.17	8.09	6.15	5.30
9	33.6	11.30	10.03	8.85	6.73	5.80
10	35.5	11.95	10.61	9.35	7.11	6.13

Table 6. Unit delivery cost according to regional attribute.

Service Region	Unit Delivery Cost			Unit Delivery Cost after Collaboration	
	A	B	C	C2 (25%)	C1 (30%)
1	1.43	1.31	1.21	1.02	0.93
2	1.63	1.49	1.36	1.14	1.04
3	1.76	1.61	1.47	1.22	1.11
4	1.83	1.67	1.52	1.26	1.14
5	1.96	1.79	1.63	1.34	1.21
6	2.23	2.03	1.84	1.50	1.35
7	2.43	2.21	2.00	1.62	1.45
8	2.57	2.33	2.10	1.70	1.52
9	2.77	2.51	2.26	1.82	1.62
10	2.91	2.63	2.37	1.90	1.69

Table 7. Optimal solution for max–min criterion (A = 5%, B = 10%, C = 15%).

Region	1	2	3	4	5	6	7	8	9	10
x_{Aj}	0	0	0	0	0	0	0	0	1	1
x_{Bj}	0	1	0	1	1	0	0	0	0	0
x_{Cj}	1	0	1	0	0	1	1	1	0	0

5.2.1. Collaboration Scenario 1: Market Density of Participating Companies (5%, 10% and 15%)

In regions 9 and 10, company A is selected for the last mile delivery service. Company B covers the regions 2, 4, and 5, and company C is responsible for the regions 1, 6, 7, and 8. The number of service regions for each company is 2, 3, and 5, respectively. The values of objective function of companies A, B, and C are g_A = 303.5, g_B = 384.1, and g_C = 439.5.

5.2.2. Collaboration Scenario 2: Market Density of Participating Companies (5%, 5% and 20%)

The second scenario included the collaboration among two small-sized companies and one major company.

As shown in Table 8, we calculated the costs when collaboration is formed among the companies with market density of 9%, 10%, and 11%. Table 9 shows companies A and B only cover two regions each, while company C covers a total of six regions. The profit for companies A, B, and C are g_A = 91.3, g_B = 91.3, and g_C = 285.7.

Table 8. Data for company A, B, and C (A = 5%, B = 5%, C = 20%) and unit delivery cost according to regional attribute.

Region	d1	d2	d3	D (=d1 + d2 + d3)	cc1	cc2	cc3	C2	C1
	5%	5%	20%		5%	5%	20%	25%	30%
1	45	45	180	270	1.43	1.43	1.11	1.02	0.93
2	43	43	171	257	1.63	1.63	1.25	1.14	1.04
3	42	42	166	249	1.76	1.76	1.34	1.22	1.11
4	41	41	163	245	1.83	1.83	1.38	1.26	1.14
5	40	40	159	238	1.96	1.96	1.48	1.34	1.21
6	37	37	150	225	2.23	2.23	1.66	1.50	1.35
7	36	36	144	216	2.43	2.43	1.80	1.62	1.45
8	35	35	140	210	2.57	2.57	1.89	1.70	1.52
9	34	34	135	202	2.77	2.77	2.03	1.82	1.62
10	33	33	132	197	2.91	2.91	2.12	1.90	1.69

Table 9. Optimal solution for max–min criterion (A = 9%, B = 10%, C = 11%).

Region	1	2	3	4	5	6	7	8	9	10
x_{Aj}	0	0	0	0	0	0	0	1	1	0
x_{Bj}	0	0	0	0	0	0	1	0	0	1
x_{Cj}	1	1	1	1	1	1	0	0	0	0

5.2.3. Collaboration Scenario 3: Market Density of Participating Companies (9%, 10% and 11%)

The third scenario included the collaboration among three medium-sized companies. Table 10 shows the cost reduction when collaboration is formed and the market density increases. From Table 11, it can be found that five regions are covered by company A, three by company B, and two by company C. The profit for companies A, B, and C are g_A = 373.9, g_B = 383.6, and g_C = 373.9.

Table 10. Data for companies A, B, and C (A = 9%, B = 10%, C = 11%) and unit delivery cost according to regional attribute.

Region	d1	d2	d3	D (=d1 + d2 + d3)	cc1	cc2	cc3	C2	C1
	9%	10%	11%		9%	10%	11%	25%	30%
1	81	90	99	270	1.33	1.31	1.29	1.02	0.93
2	77	86	94	257	1.52	1.49	1.47	1.14	1.04
3	75	83	91	249	1.64	1.61	1.58	1.22	1.11
4	74	82	90	245	1.70	1.67	1.64	1.26	1.14
5	71	79	87	238	1.82	1.79	1.76	1.34	1.21
6	67	75	82	225	2.07	2.03	1.99	1.50	1.35
7	65	72	79	216	2.25	2.21	2.16	1.62	1.45
8	63	70	77	210	2.37	2.33	2.28	1.70	1.52
9	61	67	74	202	2.56	2.51	2.46	1.82	1.62
10	59	66	72	197	2.68	2.63	2.57	1.90	1.69

Table 11. Optimal solution for max–min criterion (A = 9%, B = 10%, C = 11%).

Region	1	2	3	4	5	6	7	8	9	10
x_{Aj}	1	0	1	0	0	1	1	1	0	0
x_{Bj}	0	1	0	1	1	0	0	0	0	0
x_{Cj}	0	0	0	0	0	0	0	1	1	0

5.2.4. Collaboration Scenario 4: Market Density of Participating Companies (5%, 12% and 13%)

The last scenario considers collaboration among one company with low market density and two medium-sized companies. In Table 12, the reduced costs were calculated in each region after collaboration. Table 13 shows that company A covers 3 regions, company B covers 4 regions, and company C covers 3 regions. The profit for companies A, B, and C are g_A = 347.0, g_B = 424.4, and g_C = 367.5.

Table 12. Data for companies A, B, and C (A = 5%, B = 12%, C = 13%) and unit delivery cost according to regional attribute.

Region	d1	d2	d3	D (=d1 + d2 + d3)	cc1	cc2	cc3	C2	C1
	5%	12%	13%		5%	12%	13%	25%	30%
1	45	108	117	270	1.43	1.27	1.25	1.02	0.93
2	43	103	111	257	1.63	1.44	1.41	1.14	1.04
3	42	100	108	249	1.76	1.55	1.53	1.22	1.11
4	41	98	106	245	1.83	1.61	1.58	1.26	1.14
5	40	95	103	238	1.96	1.72	1.69	1.34	1.21
6	37	90	97	225	2.23	1.95	1.91	1.50	1.35
7	36	86	93	216	2.43	2.12	2.08	1.62	1.45
8	35	84	91	210	2.57	2.24	2.19	1.70	1.52
9	34	81	88	202	2.77	2.41	2.36	1.82	1.62
10	33	79	85	197	2.91	2.52	2.47	1.90	1.69

Table 13. Optimal solution for max–min criterion (A = 5%, B = 12%, C = 13%).

Region	1	2	3	4	5	6	7	8	9	10
x_{Aj}	0	0	1	1	1	0	0	0	0	0
x_{Bj}	1	1	0	0	0	1	1	0	0	0
x_{Cj}	0	0	1	1	1	0	0	0	0	0

6. Discussion

6.1. Customer Service Quality

According to the LMF suggested in this paper, the change in travel time with the variation of market density can be confirmed. In other words, an increase in market density reduces the travel time, and this can eventually lead to a reduction of delivery time of the delivery service drivers.

Boyer studied how customer density and delivery window pattern affect the efficiency of last mile delivery [4]. However, a model was not proposed in this study. Instead, the study showed how customer density and delivery window patterns change last mile delivery time through simulation. In this paper, demand points in delivery area are randomly generated through GA, and this generating process was carried out 100 times for each of the experiments to obtain LMF, which is the approach that reflects a more realistic delivery process.

This signifies that the delivery carriers can handle more quantity within their total working time and increase customer service satisfaction at the same time. However, a decrease in market density means an increase in travel time and decrease in delivery quantity, which may lead to lower customer service quality.

In the previous studies, the travel time was generally calculated through delivery network design and was converted to cost values. The optimization for delivery network design has been studied for a long time. In this paper, however, we developed a last mile delivery function to calculate the travel time while considering the market density. There are studies that consider the effect of the market density in last mile delivery service, but these studies only performed simulation to achieve managerial insights. In this paper, we propose LMF and a pricing model, which can be considered as the more realistic last mile delivery pricing model.

6.2. Pricing Model

Since travel cost is obtained through LMF, it is possible to examine the effect of market density on price and profit, which satisfies the establishment of the pricing model in this paper. In addition, since the existence of the optimal solution in the pricing model is proven through differentiation, the solution approach is appropriate.

From the results of the sensitivity analysis in Section 5, we examined how the optimal price and profit change when the labor cost, daily working time, and total delivery demand in certain regions differ.

Nowadays, conflict between company and delivery workers is becoming aggravated. Delivery workers are demanding more labor costs and shorter working time while a company tries to adjust these elements to earn more profit. Other than labor cost and total working time, the variation of total delivery demand in a region affects the optimal price and profit. The numerical example in Section 5 shows that when the market density decreases, the price increases and the profit decreases. In addition to the effect of labor cost and working time, a company can use the proposed pricing model as the guideline for making better investment decision to expand the capacity of terminal facilities.

6.3. Collaboration Model

Small and medium-sized express delivery companies, who have a hard time investing, may use the proposed collaboration model to decide whether to collaborate with other companies and with which companies to collaborate.

For the collaboration model, max–min criteria is used to solve the objective function regarding incremental profit of participating companies. Although max–min criteria may result in smaller total collaboration pie, since the difference in profit allocation among the participating companies is the smallest with max–min criteria, it is the method that can raise the satisfaction of companies that participate in collaboration.

The proposed model showed that profit occurs when a terminal and delivery volume is shared through collaboration. In addition, we suggested four different types of collaboration, which considers the difference in market density of participating companies. In Section 5, the profit from collaboration showed difference depending on the market density of participating companies. Therefore, with the results from the numerical example, a company can make the right decision to find right cooperator to achieve the maximum profit.

Also, through collaboration, companies can reduce travel cost and other costs such as terminal operation cost. Most small and medium-sized companies do not earn enough profit due to big investments in building new terminals or developing new services. Therefore, the proposed collaboration model is a win–win and sustainable solution for small and medium-sized companies in the long term. In addition, collaboration among companies can solve environmental problems by reducing carbon emissions during delivery.

7. Conclusions

While the express delivery service market has been steadily increased according to rapid increase in business-to-consumer (B2C) demand, delivery service companies have to overcome more severe competition in the market. In order to survive in the competitive delivery service environment, they have made many efforts to establish several strategies such as service network optimization, efficient flow management, increased terminal productivity, etc. Nowadays, a quick response has been recognized as an index for representing customer satisfaction levels. It makes the express delivery service companies apply themselves to the last mile delivery process in a delivery service.

This study suggested pricing as well as collaboration models for increasing the competitiveness of delivery companies, based on the time-market density model. In the pricing model, a procedure for finding an optimal price to expand delivery service market was introduced. A last mile delivery time function of market density was also derived with GA-based simulation results of the traveling salesman problem with randomly generated customers. In addition, a collaboration model was proposed as another strategy against the difficult market situation to mediate service price. A multi-objective integer programming problem was developed and solved based on the max–min criterion. The applicability and efficiency of two proposed models were demonstrated through an illustrative numerical example. It will be beneficial to conduct case studies with real data collected from express delivery service companies.

The solution procedures for proposed models have limitations. In the pricing model, we mainly focused on the travel cost. By using LMF, a more realistic last mile delivery cost was calculated. However, we considered costs other than travel cost as constant value. In the real world, as market density differs other costs such as terminal operation costs can be affected. Including the total process of express delivery into the proposed model can make the suggested pricing model more realistic.

The suggested collaboration model considered incremental profit which assumed that collaboration always secures profit for participating companies. However, as shown in Section 5, in some cases, based on the market density of participating companies, collaboration does not always guarantee the satisfaction of companies. In this paper, we used max–min criteria to calculate the profit for participating companies. Max–min criteria have limitations because this is a method of calculating the minimum profit of a whole collaboration while reducing the imbalance of profit between participating companies. Other methodologies used game theory studies for more reasonable distribution of total profit to increase the satisfaction of participating companies.

In future studies, several types of demand functions of price will be considered in pricing model. In addition, we can apply our suggested time-density model and pricing model to other express delivery research to modify it, considering the expected profit from forming different types of hub network. Also, collaborations model will be developed and compared with each other under various criteria such as max-sum. Furthermore, development of fair allocation methods of coalition profit will be included in order to sustain long-term collaboration.

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Appendix A

In this section, the procedure for finding an optimal price to maximize the profit is explained. From (5) and (6) $Z(p)$ can be represented as:

$$Z(p) = \left(p - w \times \frac{(0.00005)\left(\frac{a-bp}{N}\right)^2 - 0.8347\left(\frac{a-bp}{N}\right) + 0.3764}{T} \right)(a-bp) - K \quad \text{(A1)}$$

For simplicity of notation, the constant term K in (A1) is ignored. For finding an optimal price to maximize $Z(p)$, its 1st-order derivative, $Z\ (p)$ is given by:

$$\begin{aligned} Z'(p) = & -\left(\frac{w\left((0.8347)\frac{b}{N} - (0.0001)\frac{b(a-bp)}{N^2}\right)}{T} - 1 \right)(a-bp) \\ & -b\left(x - \frac{w\left((0.00005)\frac{(a-bp)^2}{N^2} - (0.8347)\frac{(a-bp)}{N} + 0.3764\right)}{T} \right) \end{aligned} \quad \text{(A2)}$$

By $Z'(p) = 0$, two solutions, p_1 and p_2 are obtained as:

$$p_1 = \frac{1}{3b^2w}\Big(20000N^2T - 16694Nbw + 3abw - 10000N\sqrt{4N^2T^2 - 6.6776NTbw + 0.0006aTbw + 2.78667052b^2w^2}\Big) \quad \text{(A3)}$$

$$p_2 = \frac{1}{3b^2w}\Big(20000N^2T - 16694Nbw + 3abw + 10000N\sqrt{4N^2T^2 - 6.6776NTbw + 0.0006aTbw + 2.78667052b^2w^2}\Big) \quad \text{(A4)}$$

Note that the co-efficient of p in (A1) is positive since the parameter values $N,\ T,\ a,\ b,\ w > 0$, the smaller solution p_1 can be the candidate for the optimal price.

By solving $Z(p) = 0$, we can get three solutions:

$$\frac{a}{b},\ \frac{1}{b^2w}\Big(10000N^2T - 8347Nbw + abw - 10000N\sqrt{N^2T^2 - 1.6694NTbw + 0.0002aTbw + 0.69664881b^2w^2}\Big), \quad \text{(A5)}$$

$$\frac{1}{b^2w}\Big(10000N^2T - 8347Nbw + abw + 10000N\sqrt{N^2T^2 - 1.6694NTbw + 0.0002aTbw + 0.69664881b^2w^2}\Big)$$

Since all the parameter values are positive and the price must be a positive value, it is found that:

$$\frac{a}{b} > \frac{1}{b^2w}\Big(10000N^2T - 8347Nbw + abw - 10000N\sqrt{N^2T^2 - 1.6694NTbw + 0.0002aTbw + 0.69664881b^2w^2}\Big).$$

This proves that p_1 is the optimal price.

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Bayesian Methods for Reliability Demonstration Test for Finite Population Using Lot and Sequential Sampling

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Abstract: The work proposed a reliability demonstration test (RDT) process, which can be employed to determine whether a finite population is accepted or rejected. Bayesian and non-Bayesian approaches were compared in the proposed RDT process, as were lot and sequential sampling. One-shot devices, such as bullets, fire extinguishers, and grenades, were used as test targets, with their functioning state expressible as a binary model. A hypergeometric distribution was adopted as the likelihood function for a finite population consisting of binary items. It was demonstrated that a beta-binomial distribution was the conjugate prior of the hypergeometric likelihood function. According to the Bayesian approach, the posterior beta-binomial distribution is used to decide on the acceptance or rejection of the population in the RDT. The proposed method in this work could be used to select item providers in a supply chain, who guarantee a predetermined reliability target and confidence level. Numerical examples show that a Bayesian approach with sequential sampling has the advantage of only requiring a small sample size to determine the acceptance of a finite population.

Keywords: quality level; supply chain; reliability demonstration test; Bayesian approach; conjugacy; beta-binomial distribution; sequential sampling; one-shot devices; finite population

1. Introduction

Most manufacturers consider sustainability when developing and marketing new products. Sustainability itself is significantly affected by strategic decision-making during the product development stage. The importance of this has been illustrated by Hallstedt et al. [1] and Michelon et al. [2], who presented an approach to assessing sustainability integration in a strategic decision-making system for product development, whilst Siva et al. [3] built a conceptual framework designed to build sustainability capabilities by combining product development and quality management. In safety-related industries, such as automotive airbags and fire extinguishers, customers see product quality as a key success factor; thus, after developing a new product, quality levels must be assessed. In supply chain management, risk of quality failure must be managed. The results of quality failure at the upstream supply chain can be overwhelming. This is due to the interdependence of the supply chain partners [4]. Indeed, unless adequate quality assessment is conducted during the development stage, the performance of new products cannot be guaranteed during the operational stage. However, one-shot devices are not reusable after testing, and it is therefore necessary to select of item providers in a supply chain that satisfy customer demand for quality using as few products as possible during the quality assessment stage.

Reliability demonstration tests (RDTs) are widely used to determine whether a designed product meets a predetermined minimum reliability level under various engineering settings. Satisfying minimum reliability levels can be taken as a guarantee of a product's quality. It is important that an RDT be designed to reflect the specific test environment, which includes the reliability metrics, the test target, the sampling method, and sample size [5,6].

Reliability metrics are summary statistics calculated from sample data that represent the degree to which a system can be considered reliable [7,8]. Previous RDT approaches have employed two types of reliability metrics, i.e., failure time and failure count, to assess system failure [9,10]. Failure time includes mean time to failure (MTTF), mean time between failure (MTBF), and B_{10} life (i.e., the period during which no more than 10% of the product population is expected to fail). Failure count is based on the reliability–confidence level (R-C), which serves as a binary measure of success or failure [11,12]. These two types of metrics have been used to assess continuously operating test targets, such as tanks or submarines, which are classified as either repairable or non-repairable, and with one-shot devices, such as rockets or missiles, which are all non-repairable.

Past research on RDTs has mainly focused on determining the minimum sample size required to accept a population [13]. Recent studies have tended to establish more realistic settings when determining the optimal sample size. For example, RDTs often use a fixed R-C level as a reliability metric for a given testing period. However, Chen et al. [14] employed an approach in which RDTs were able to meet customer requirements by incorporating different times coupled with different R-C levels. For the convenience of RDT sample size calculation, most RDT research has been conducted based on the specific characteristics of a single component with no prior information about the population and with independent samples. However, Guo [15] employed an RDT for one-shot devices that used multiple components and a hybrid model of Bayesian and variance propagation. In addition, in a study by Kleyner et al. [11], the optimal sample size was calculated using a mixed prior and between-product similarity.

A binomial distribution is frequently used to model failure count data [14,16–19]. Binomial RDTs are mainly used when the test data is binary; they are particularly useful for the destructive and time-consuming sample testing of one-shot devices, such as bullets, fire extinguishers, grenades, and missiles. Based on past experience in product development and test environments for these one-shot devices or components, designers aim to meet a pre-determined reliability target.

2. Inference Method—Bayesian and Non-Bayesian Approaches

The non-Bayesian method is a traditional approach to statistical inference. When previous experience and data are not available for RDTs, many sample tests are required to demonstrate high reliability with high confidence levels. However, the number of one-shot devices used in real-life testing is usually very small due to costs, and the non-Bayesian approach to statistical inference does not explain past experience [10].

To overcome these limitations, the Bayesian approach has been adopted because it combines subjective judgment or prior experience, with data from test samples to predict the probabilistic characteristics of a population. That is, the Bayesian approach uses a combination of previous experience and new test data when applying statistical tools to assess reliability metrics. In the Bayesian approach, a posterior distribution is derived from a prior distribution and a likelihood function, and the RDTs are conducted using the derived posterior distribution. When new sample data is added, this posterior distribution is then employed as a prior distribution in the process of producing a new posterior distribution. This cyclical use of the posterior distribution as a prior distribution in the RDTs of a finite population is known as the Bayesian learning process [20]. Using this method, it is particularly important to determine the optimal sample size for binomial RDTs, for one-shot devices [11,15,16,21].

As mentioned above, when using the Bayesian approach, it is necessary to employ both a likelihood function and a prior distribution to estimate the posterior distribution. A natural-conjugate prior distribution is employed as a likelihood function when they are of the same functional form [22–25]. Applying Bayesian statistics and using prior knowledge accumulated in previous stages of the design process, also helps to reduce the sample size required to meet a product's reliability specifications [11]. These studies use a binomial distribution as binary sample data. In particular, for one-shot devices, a binomial distribution is often applied to test results because the outcome is either a success or a failure.

However, the use of a binomial distribution as a likelihood function without considering population properties such as size, defective ratio, and sampling data type can be problematic. For instance, if the defective ratio within a population (q) is unknown, random samples cannot possibly be independent. This is because q can be updated using sampled data, which means that samples are no longer probabilistically independent. Furthermore, a binomial distribution is used when samples are taken from an infinite population or with replacement from a finite population. However, sampling without replacement is conducted for the testing of one-shot devices.

In this work, a hypergeometric distribution is adopted as a likelihood function for a finite population consisting of one-shot devices. According to the Bayesian framework, it can be mathematically demonstrated that a beta-binomial distribution is the conjugate prior of a hypergeometric likelihood function. A posterior beta-binomial distribution is then used to make decisions in RDTs.

3. Scope of the Proposed RDT Process

Notation:

N^* = infinite population size
N = finite population size
X^* = number of defective items in N^*
X = number of defective items in N
n = sample size selected from a population of size N
k = number of defective items from sample size n
R = population reliability
CL = confidence level
q = defective ratio within population N, which equals X^*/N^*

This work assumes that lot sampling is used to simultaneously test lots of size n, while sequential sampling is employed for testing one item at a time. RDTs require that the sampling method, sample size, data type, and reliability metrics be determined based on the specific test environment. This environment may have a finite population, the presence of prior information, and restrictions of time and money in the sampling process; however, surprisingly few studies have systematically examined the RDT process with respect to these important factors. The choice of an optimal RDT strategy is of great practical importance in product development. In this respect, the R-C measure serves as a suitable reliability metric for the acceptance or rejection of a population when the test result for an individual item from that population is classified as a success or a failure.

Figure 1 illustrates the scope of the present work, which deals with a finite population of single-component products assessed using failure count data. In order to determine the optimal sample size, lot and sequential sampling are adopted for the RDTs, while the non-Bayesian and Bayesian inference approaches are compared.

Most previous RDT studies calculate the initial sample size n for success-based testing. In this approach, the population is accepted when no defective items are found within a sample of n items. Though success-based testing is regularly employed in industry in the hopes that a sample will contain no defective items and the population will be accepted, defective items are often found during testing due to the fact that the defective ratio q within the population is unknown.

It remains unclear exactly what RDT process should be followed to determine the acceptance of a population when defective items appear in a sample. It is thus necessary to develop an RDT process that has a suitable method for determining the number of additional items from the population that need to be sampled when a defective item appears during testing, while simultaneously considering specific sampling methods, such as lot or sequential sampling. It is particularly important to consider both lot and sequential sampling, because a sufficient sample size for RDTs cannot be guaranteed in new product development projects.

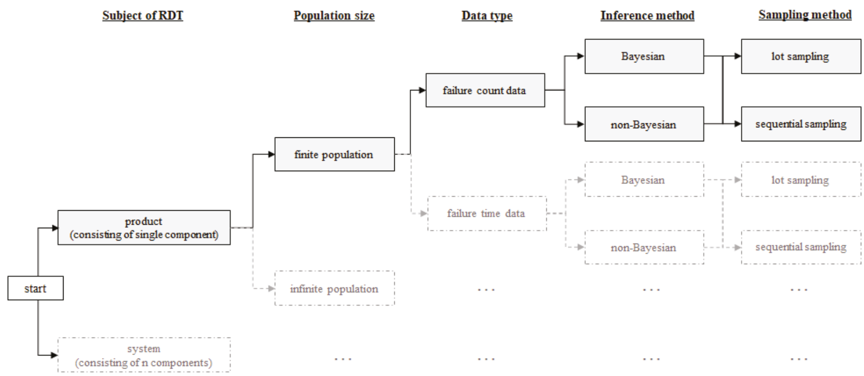

Figure 1. Scope of the current work.

One technical aspect of note in the present work is that the sampling results are immediately used to obtain a posterior distribution from the prior distribution of the population's parameters using the Bayesian approach. Using the natural-conjugate prior distribution of the likelihood function allows the posterior distribution's functional form to be expressed easily.

Starting with a population of size N with X defective items within the population, the population size and the number of defective items will be updated after the sampling process in the following manner: $N, N - n_1, N - n_2, \ldots$ and $X, X - k_1, X - k_2, \ldots$, where n_i is the i-th sample and k_i is the number of defective items in n_i. Figure 2 presents the proposed RDT process for calculating the additional number of items that need to be sampled after detecting defective items during success-based testing.

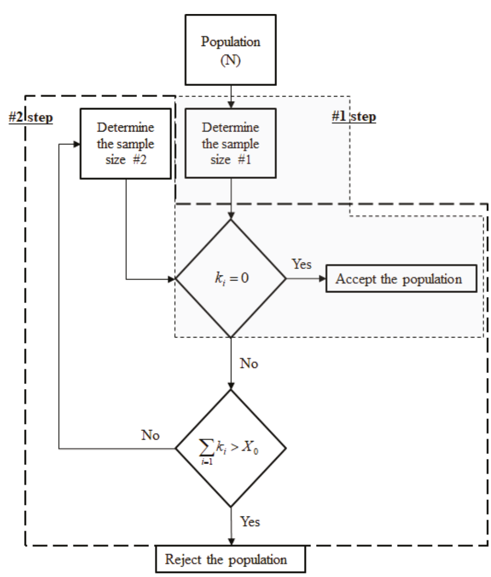

Figure 2. The proposed reliability demonstration test (RDT) process.

Whether the population is finite or infinite, and whether prior information is present or absent, are established in the "Population" step. In the "#1 step," the initial sample size n is determined using the non-Bayesian or Bayesian approach, as explained in Sections 3 and 4. This initial sample size is calculated using information on population size, confidence level, population reliability, and the inference method without test data. An RDT is then conducted with initial sample size n. The population is accepted when no defects are detected in the initial sample. If the number of defective items k in the initial sample is not 0, the "#2 step" is implemented, in which the value of n (e.g., the first sample size n, the second sample size n) can be obtained from N and the maximum number of allowable defective items X_0 using both non-Bayesian and Bayesian approaches. If the accumulated number of defects k in the sample exceeds X_0, the population is rejected. The n calculated in the "#2 step" can vary according to the sampling method (i.e., lot or sequential). Therefore, the optimal sample size required for RDTs depends on the sampling method, so both lot and sequential sampling must be considered when determining the sampling size.

4. Sampling Distributions for a Finite Population

The present work employs an RDT for a finite population, and non-Bayesian and Bayesian approaches to determine the optimal sample size. When sampling from a finite population, the size of the population N and the number of defective items X in that population can be written as $N, N - n_1, N - n_2, \ldots$ and $X, X - k_1, X - k_2, \ldots$, respectively, where is the i-th sample and k_i is the number of defective items in n_i. A Bayesian approach can be used to calculate $p(X = x)$ when conducting an RDT for a finite population. In this approach, the multiplication of the prior distribution $p(X = x)$ and the likelihood function $p(data|X = x)$ is proportional to the posterior distribution $p(X - k = x - k|data)$, as expressed in Equation (1):

$$p(X - k = x - k|data) \propto p(data|X = x)p(X = x). \tag{1}$$

A binomial probability distribution can be employed under the assumption that either the size of the population is infinite or the samples are independent. When the population is finite and the samples are dependent, a hypergeometric probability distribution should be employed. The present work is particularly interested in RDTs for a finite population. Thus, $p(data = k|X = x)$ represents the probability distribution of the samples from a finite population and is expressed as a hypergeometric distribution in Equation (2):

$$p(data = k|X = x) = \frac{\begin{pmatrix} x \\ k \end{pmatrix}\begin{pmatrix} N-x \\ n-k \end{pmatrix}}{\begin{pmatrix} N \\ n \end{pmatrix}} = \frac{\begin{pmatrix} n \\ k \end{pmatrix}\begin{pmatrix} N-n \\ x-k \end{pmatrix}}{\begin{pmatrix} N \\ x \end{pmatrix}}, k = 0, 1, \cdots, \min(n, x). \tag{2}$$

This work mathematically calculates the conjugacy between the hypergeometric distribution and the beta-binomial distribution, and then determines the optimal sample size. The prior distribution $p(X = x)$ is calculated to estimate the posterior distribution $p(X - k = x - k|data)$. It is reasonable to expect that this can be obtained from the relationship between the sample and population sizes, as illustrated in Figure 3, given the N^* of a large population regarded to be infinite, the N of a finite population, X^* (the total number of defective items in N^*), X (the number of defects in N), and k (the number of defective items in the sample n). The finite population is assumed be a subset of the infinite population.

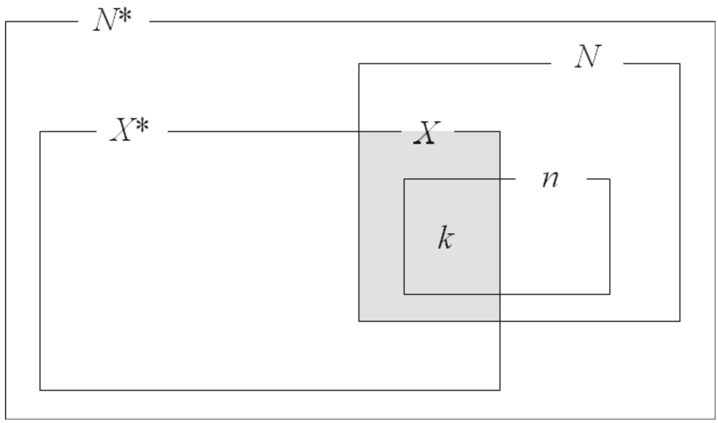

Figure 3. Relationship between the sample and population sizes.

The conjugacy between the hypergeometric and beta-binomial distributions is calculated using the first sample (i = 1), as shown in Appendix A [26]. The conjugacy is then verified for i = 2, 3, 4 . . . through the sequential calculation of the posterior distribution. The generalizations of Equations (A6) and (2) correspond to Equations (3) and (4), respectively, where $data_i$ denotes the number of defective items k_i from n_i.

$$p_i((X - \sum_{j=1}^{i} k_j) = (x - \sum_{j=1}^{i} k_j)|data_i) = \frac{P(data_i|X=x)P_{i-1}(X=x)}{\sum_x P(data_i|X=x)P_{i-1}(X=x)},$$
$$x = \sum_{j=1}^{i-1} k_j, \cdots, N - \sum_{j=1}^{i-1} (n_j - k_j), i = 2, 3, 4, \cdots, \tag{3}$$

$$p(data_i|(X - \sum_{j=1}^{i-1} k_j) - (x - \sum_{j=1}^{i-1} k_j)) = \frac{\begin{pmatrix} x - \sum_{j=1}^{i-1} k_j \\ k_i \end{pmatrix} \begin{pmatrix} N_i - x + \sum_{j=1}^{i-1} k_j \\ n_i - k_i \end{pmatrix}}{\begin{pmatrix} N_i \\ n_i \end{pmatrix}},$$
$$N_i = N - \sum_{j=1}^{i-1} n_j. \tag{4}$$

Combining Equations (A7), (3), and (4) leads to a generalized formula for the i-th posterior distribution, shown in Equation (5):

$$p_i((X - \sum_{j=1}^{i} k_j) = (x - \sum_{j=1}^{i} k_j)|data_i) = \begin{pmatrix} N - \sum_{j=1}^{i} n_j \\ X - \sum_{j=1}^{i} k_j \end{pmatrix} \frac{\beta(a+x, b+N-x)}{\beta(a + \sum_{j=1}^{i} k_j, b + \sum_{j=1}^{i} (n_j - k_j))}. \tag{5}$$

5. Sample Size Based on the Proposed RDT

Figure 4 presents the process adopted by the present work to determine the optimal sample size. X_0 is the maximum number of allowable defective items, and the initial sample size n is obtained from success-based testing (at k = 0) through a series of calculations using a finite population and the R-C measure.

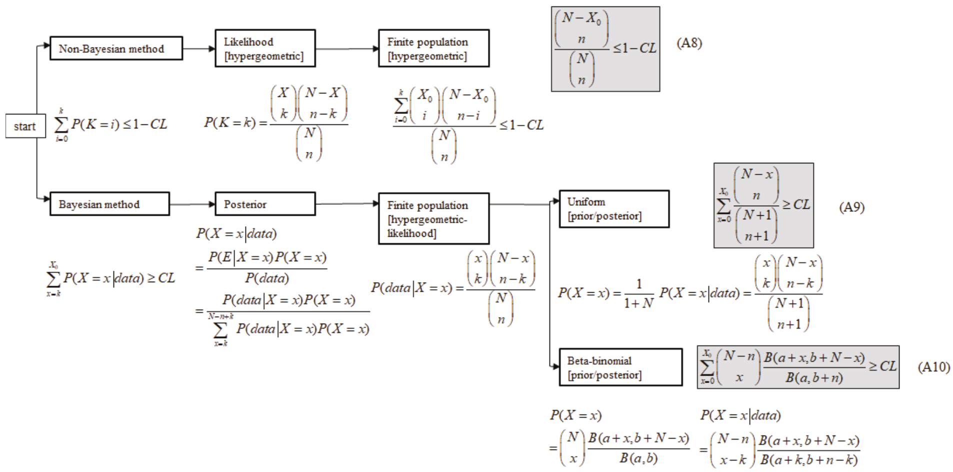

Figure 4. Classification of non-Bayesian and Bayesian methods for the determination of sample size.

As shown in Table 1, a population is accepted with 95% reliability and a 90% confidence level for the non-Bayesian approach, when 37 items selected from that population are found to be free of defects. It should be noted that, in the absence of prior information regarding the parameter values for the beta-binomial distribution, it is assumed that $a = 1$ and $b = 1$ [10].

Table 1. Results for the n values by method (95% reliability and 90% confidence level).

Method	Prior	Sampling	Initial n	First n	Second n	Third n
Non-Bayesian	no prior	lot	37	27 (total 64)	19 (total 83)	12 (total 95)
		sequential	37	34 (total 57) (failure at 23rd item)	28 (total 76) (failure at 48th item)	27 (total 87) (failure at 60th item)
Bayesian	uniform	lot	31	25 (total 56)	19 (total 75)	13 (total 88)
		sequential	31	28 (total 51) (failure at 23rd item)	22 (total 70) (failure at 48th item)	21 (total 81) (failure at 60th item)
	beta-binomial	lot	31	19 (total 50)	16 (total 66)	13 (total 79)
		sequential	31	27 (total 50) (failure at 23rd item)	18 (total 66) (failure at 48th item)	19 (total 79) (failure at 60th item)

Table 1 summarizes the series of calculations used to determine optimal sample size in the RDT process, given $N = 100$, 95% reliability, and a 90% confidence level target requirement. Here, "Initial n" represents the optimal sample size for success-based testing in the absence of sample data. "First n" in Table 1 is the number of additional items that are required for testing when the initial n contains a defective item. The computation of the optimal sample size is outlined in Appendix B. The value of the initial n differs, depending on which inference method is used to determine the sample size (i.e., non-Bayesian or Bayesian). Once the initial n has been calculated, different sampling methods produce different values for the first n.

Numerical examples show that a beta-binomial Bayesian approach with sequential sampling has the advantage of requiring only a small sample size when determining the acceptance of a finite population. When the beta-binomial Bayesian method is applied, the total number of additional items required for sampling is the same for both lot and sequential sampling, when determining the acceptance or rejection of a finite population. However, the sample size calculated for sequential sampling was the same as or smaller than that obtained for lot sampling because lot sampling tests lots of size n simultaneously, and sequential sampling tests one item at a time.

6. Conclusions

The present work proposed an RDT process that is able to reflect the specific test environment, including the test target, sample size, inference method, and sampling method. Both lot and sequential sampling were considered in this RDT process because optimal sample sizes for RDTs cannot be guaranteed in test environments for new product development projects. This process was implemented when a defective item appeared during success-based testing, employing both non-Bayesian and Bayesian approaches based on R-C failure data for one-shot devices. This work considered the samples to not be independent. Thus, a hypergeometric distribution was adopted as a likelihood function for a finite population consisting of one-shot devices. Based on the Bayesian framework, the conjugacy between the hypergeometric likelihood function and a beta-binomial distribution was mathematically calculated. The posterior beta-binomial distribution was used to decide in the RDT, on whether to accept or reject the population.

The results indicated that a beta-binomial Bayesian approach with sequential sampling has the smallest optimal sample size when determining the acceptance or rejection of a finite population. The proposed RDT process can thus be used in similar test environments, such as in new product development projects.

The present work was founded on the absence of prior information about the target population. In future research, this RDT process could be extended to examine additional ways to decrease the sample size required for RDTs. One possible option in this respect could be changing the parameter values for the prior distribution based on prior information or expert opinion on the population.

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Appendix A

In this Appendix A, the prior distribution $p(X = x)$ is calculated to estimate the posterior distribution $p(X - k = x - k|data)$. Given the assumption that the values X^*, N^* are close to unlimited, the defective ratio is expressed as q (or $\frac{X^*}{N^*} \to q$). The conditional probability of X given q from N is expressed as $bi(N, q)$ in Equation (A1). q can be written as $beta(a, b)$ in Equation (A2), and $p(X = x)$ denotes the unconditional probability distribution. Combining Equations (A1) and (A2), Equation (A3) can be expressed as $bet - bin(N, a, b)$ in Equation (A4).

$$p(X = x|q) = \binom{N}{x} q^x (1-q)^{N-x}, \tag{A1}$$

$$P(q) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} q^{a-1} (1-q)^{b-1}, \tag{A2}$$

$$p(X = x) = \int_0^1 p(X = x|q)p(q)dq, \tag{A3}$$

$$p(X = x) = \binom{N}{x} \frac{\beta(a + x, b + N - x)}{\beta(a, b)}, x = 0, 1, \cdots, N. \tag{A4}$$

The replacement of N with n and x with k in Equation (A4) can be expressed as Equation (A5):

$$p(data = k) = \binom{n}{k} \frac{\beta(a + k, b + n - k)}{\beta(a, b)}, k = 0, 1, \cdots, n. \tag{A5}$$

Using Bayes' theorem, the value of the posterior distribution can be expressed as Equation (A6):

$$p(X - k = x - k|data) = \frac{p(data = k|X = x)p(X = x)}{p(data = k)}. \tag{A6}$$

Based on Equations (2), (A4), and (A5), the form of the posterior distribution is identical to that of the beta-binomial distribution, given that k is the number of defective items in a sample. In other words, the parameters for the prior distribution $p(X = x)$ and posterior distribution $p(X - k = x - k|data)$ are updated from $bet - bin(N, a, b)$ and $bet - bin(N - n, a + k, b + n - k)$, respectively. The foregoing shows the conjugacy between the hypergeometric distribution and the beta-binomial distribution in Equation (A7):

$$p(X - k = x - k|data) = \binom{N - n}{x - k} \frac{\beta(a + x, b + N - x)}{\beta(a + k, b + n - k)}, x = k, k + 1, \cdots, N - (n - k). \tag{A7}$$

Appendix B

Appendix B describes the calculation process and equations used to compute the results of Table 1. The non-Bayesian method uses Equation (A8) and the Bayesian method uses Equations (A9) and (A10), to calculate the optimal sample required for RDT. Table 1 shows some of the simulated data assuming defective items were found in the initial samples. Using Equations (A8)–(A10) and the proposed RDT process, we can calculate the optimal n in RDT under different conditions.

$$\frac{\binom{N - X_0}{n}}{\binom{N}{n}} \leq 1 - CL, \tag{A8}$$

$$\sum_{x=0}^{X_0} \frac{\binom{N - x}{n}}{\binom{N + 1}{n + 1}} \geq CL, \tag{A9}$$

$$\sum_{x=0}^{X_0} \binom{N - n}{x} \frac{B(a + x, b + N - x)}{B(a, b + n)} \geq CL. \tag{A10}$$

As a numerical example, for a population size of N = 100 with 95% reliability (R) and a 90% confidence level (CL), the initial n was calculated to be 37 and 31 for the non-Bayesian (using Equation (A8)) and Bayesian (by using Equations (A9) and (A10)) approaches, respectively, in success-based testing (k = 0). Based on Equation (A8), the optimal sample sizes (n = 37) required for the success-based testing of a population size of N = 100 (R = 0.95, CL = 0.9) are given in Table 1.

When adopting a sequential sampling approach, if the first defective item is the 23rd item of the initial sample (either 37 or 31), $N = 100 - n$, $X_0 = 5 - k$ is updated with n = 23 and k = 1.

Based on Equations (A8) and (A9), the optimal sample sizes (first n = 34 and first n = 28) required for the success-based testing of the population $N = 77$, $X_0 = 4$ (R = 0.95, CL = 0.9) are given in Table 1. The value n = 28 is based on a Bayesian uniform distribution. Using the Bayesian beta-binomial distribution Equation (A10), n = 27 is calculated when $a = 1 + k$ and $b = 1 + n - k$, using n = 23 and k = 1.

The second n in Table 1 is the number of additional items that require testing based on the first n when a second defective item is drawn from the population, whilst the third n represents the number of additional items required for testing based on the second n when a third defective item is drawn from the population. The total n is the overall sample size required for the RDT. The mean and variation of the beta-binomial distribution are Equations (A11) and (A12). The summary statistics of the posterior distribution can be calculated using Equations (A11) and (A12).

$$E(X) = \frac{Na}{a+b}, \tag{A11}$$

$$V(X) = \frac{Nab(a+b+N)}{(a+b)^2(a+b+1)}. \tag{A12}$$

Table A1 summarizes the sensitivity of the hyperparameters from a beta-binomial distribution, in the series of calculations used to determine sample size, given N = 100, 95% reliability, and a 90% confidence level target requirement. The larger the value of hyperparameter b, the smaller the initial n.

Table A1. The sensitivity of the hyperparameters from a beta-binomial distribution.

a	1	1	1	1	1
b	1	2	3	4	5
Initial n	31	30	30	29	28

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Blockchain Practices, Potentials, and Perspectives in Greening Supply Chains

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Abstract: Blockchain technology is an inchoate technology whose current popularity is peaking. Some of the most pervasive blockchain technology use cases exist for supply chains. Sustainable, and especially green, supply chains can benefit from blockchain technology, but there are also caveats. The sustainability and environmental management research and academic literature is only starting to investigate this emergent field. This paper seeks to help advance the discussion and motivate additional practice and research related to green supply chains and blockchain technology. This viewpoint paper provides insight into some of the main dimensions of blockchain technology, an overview of the use cases and issues, and some general research areas for further investigation.

Keywords: blockchain; supply chain; green supply chain; use cases; applications

1. Introduction

Technological advancements have caused a revisiting of sustainability practices. According to ecological modernization theory, technology can help decouple environmental degradation from economic growth [1]. In some cases, technology can benefit both dimensions. As the triple-bottom-line sustainability definition includes social dimensions, whether technology can contribute to all dimensions of sustainability is unclear.

Advances in technology are broad-based and include a variety of production, information, and social technologies. These technologies include current and future developments in such disparate, but possibly interrelated, areas such as additive manufacturing, micro-factories, nanotechnology, Internet of Things (IoT), self-driving vehicles, sharing economies, and blockchain technology [2]. Each of these technologies has implications for the sustainability of organizations and especially their supply chains.

Supply chain management is critical for managing sustainability at global and local levels. Whether the focus is on environmental and green initiatives or social responsibility, the largest and deepest influences are supply chain activities. Of all technological developments, blockchain technology can have profound implications for supply chain sustainability, also known as distributed ledger technology. Although we devote a whole section to the definition of blockchain technology and general characteristics, we define it as decentralized databases or ledgers of records that are shared among networks and supply chain participants. In blockchains, records and data are secure, traceable, and auditable, and maintained on a peer-to-peer network [3]. The contribution of this paper is providing insights into the potential application of this nascent technology to facilitate green practices in supply chains. Our discussion is grounded on the current understanding of blockchain technology and green supply chain management literature. The evaluation framework used in this study was proposed by Hervani et al. [4]. This study would help managers, researchers, and practitioners to further evaluate the potential usage of blockchain technology to improve sustainability, especially along the supply chain.

To further clarify, we provide some insights into the various sustainability-oriented opportunities associated with blockchain technology use cases that occur across and within the supply chain. The supply chain activities include those occurring in upstream, internal organizational, downstream, and loop-closing functions [4]. There are similar relationships and implications for each of these activity groups, and there are also unique activity specific cases. After examples are provided, some general research questions are posited. We think this discussion furthers the need to carefully study how blockchain technology specifically, and disruptive technology in general, require more nuanced investigation in sustainable supply chain practice and research.

2. Blockchain Technology

Blockchain technology became popular through the advancement of cryptocurrency and bitcoin after the 2008 financial crisis [5]. Although the primary focus had been on financial applications, the unique characteristics of blockchain technology inspired broader use of this technology in different markets and even for non-financial business purposes. Supply chains [6], real estate [7,8], government [9], healthcare [10], and energy sector [11] use cases have been some effective applications.

Blockchain technology has a number of general characteristics. The integration of these characteristics differentiate blockchain from other similar information technologies. Unlike other business information technologies, blockchain technology uses a unique data structure that stores data as a chain of blocks. Once a new transaction is recorded on the system, it builds a block that is linked to the previous blocks, creating a chain [5].

In terms of openness and access to data, two popular types of blockchain exist: public and private. In the public blockchain, which is generally permissionless, ledgers are publicly available and anyone can record transactions and track the historical transaction on the ledgers. Popular cryptocurrencies, such as bitcoin and ether from Ethereum, were developed on public blockchains. Public blockchains require a high level of security and reliability due to the existence of anonymous users and the lack of trust among them [12].

In a private blockchain, users are known and ledgers are shared among a private group of participants. In a private or permissioned blockchain, access is restricted to a defined group of participants. A validator allows participants to join the system, provides permission to the ledgers, and maintains the privacy needs of the network [9,13]. Depending on the type of blockchain, the characteristics slightly change.

Although the main features of both blockchains may overlap and vary in some of the literature, we discuss some of the more popular characteristics. Included amongst these characteristics are decentralized databases, data security, information transparency, information immutability, and smart contracts.

2.1. Decentralized Database

Decentralization is an essential characteristic of blockchain technology. In blockchains, no central database, organization, or authority is typically involved in transactions. Decentralized databases of records allow participants in the network to directly interact via a peer-to-peer network. Every participant in the network has the same copy of the ledgers, which are updated with new information or changes in the recorded information in a decentralized manner [3].

Every update in a ledger requires consensus among the network partners. Decentralized consensus is the core of blockchain, which utilizes various algorithms such as proof of work and proof of stake to confirm the reliability of a recorded transaction. Generally, decentralized consensus includes votes or validation of the majority of participants of a network for ensuring the credibility of transactions. Public blockchains require heavy use of consensus algorithms that consume a great amount of power and energy. This characteristic contributes to environmental degradation and negatively affects sustainability values [14].

In a private or permissioned blockchain, the consensus requirement is a set of rules that is defined by the network participants for adding and updating transactions to ledgers. Consensus rules in a private network provide flexibility and ease the use of cumbersome consensus algorithms.

2.2. Security

Information is maintained as blocks within blockchain technology. Each block has a timestamp and a hash value that refers to previous blocks on the chain. Hash values have unique cryptographic structures that prevent tampering and altering the information in the blockchain [15]. Cryptography logic facilitates authentication and trading for anonymous parties, which is a necessity in public, permissionless blockchains, improving the trust and security of the system.

In a private/permissioned blockchain, the trust in the validator, who gives permission to the parties to record and trace information, plays an important role [16]. Security is improved by the decentralized structure of the blockchain. As a result of decentralization, the validity of information is examined by network members based on the consensus rules. This characteristic confines the data misuse and network manipulation. Decentralization also ensures the network is less vulnerable to hacking or crashing. The single point of failure is a common security problem of centralized databases, which has been alleviated by the use of blockchain technology [9].

The timestamp plays a critical role in the supply chain given various time-based competitive issues, such as lead time, delivery, and perishability concerns. The timestamp is also critical to traceability and information transparency.

2.3. Information Transparency

Authorized blockchain network participants maintain the same copy of a ledger, which contains a list of transactions. The ledgers are updated with the most recent approved transactions. A complete history of transactions are visible to the network members, allowing for auditability and traceability [17]. The level of transparency provided by the blockchain enhances fairness and ease of access to data within a network [3]. Transparent information removes intermediaries involved in the processes, increases efficiency, and reduces risks [15].

Growing customer demands for supply chain transparency motivate the application of blockchain technology for supply chain processes. A high degree of transparency provides fundamentals for tracking the origin and flow of products and processes, the parties involved in transactions, and transportation information. Supply chain partners from upstream to end customers can follow and audit the history of records. Since records on the blockchain are time-stamped and secure, data manipulation and fraud are detectable and traceable on the ledgers. This provides trust and reliability for supply chain partners [18]. Tracking technologies, such as radio frequency identification (RFID), the IoT, and smart devices link the physical product to the respective electronic records, creating inputs for blockchain technology that are maintained on transparent ledgers [19].

2.4. Data and Information Immutability

Blockchain data and information are immutable. Immutability means that records cannot be changed or modified without network member consensus. Participants can be confident that the history of records are reliable and unaltered. Theoretically, this feature comes from the append-only concept of the blockchain, which means records can only be added to ledgers and cannot be modified or removed. However, on a public or permissionless blockchain, where miners vote for transactions and control the system, collusion is possible if the majority of miners decide to alter or remove a transaction. Alternatively, change and removing information on a private or permissioned blockchain requires notifying the network members and follows certain agreements and approval requirements [9,16].

2.5. Smart Contracts

Smart contracts are computer codes and scripts that contain terms of contracts and business rules. Smart contracts automatically execute the terms of agreements. Smart contracts check the pre-determined conditions including rules and penalties that are agreed to by parties and trigger the related action to those conditions.

The conditions and terms of contracts are validated by network members [20]. These computer codes are self-executives seeking to eliminate human intervention in contracts. Unlike traditional contracts where trust between parties plays an important role, smart contracts remove the need for trust. Terms of contracts and the related legal actions are digitally written as computer programs and stored on the blockchain platform. The digital contracts remove human judgement from transactions. The role of intermediaries, such as financial professionals and legal people that are involved in traditional contracts, can be minimized through smart contract use. The resulting disintermediation improves efficiency and reduces the costs of business activities.

An example of smart contracts is an automatic payment that is performed when a certain regulation is met or a particular value is added to a product [3,21]. Transactions need to be verified to be added to the ledgers in blockchain technology. The process of transaction validation by network participants can be facilitated through smart contracts. The validation requirements and consensus rules can be regulated by network members and maintained as digital contracts. Smart contracts can check the pre-defined conditions for approving transactions and add them to the ledgers. Similarly, a change in the approved transactions can follow particular regulations that are stored on smart contracts. This digital transaction approval can simplify the use of blockchain technology in complex and private business networks.

3. Green and Sustainable Supply Chains: Blockchain Use Cases and Potentialities

The supply chain has numerous intra- and inter-organizational activities. Figure 1 provides a supply chain activities diagram that incorporates a closed loop perspective with some environmental sustainability dimensions [4]. The activities generally include: (1) upstream vendor/supplier management concerns, such as supplier selection and development; (2) upstream purchasing, inbound logistics, and inventory management activities; (3) internal operations and productions activities; (4) downstream activities including distribution, green marketing, and consumerism; and (5) closing-the-loop activities such as reverse logistics and the various "Re's", such as recycle, reuse, remanufacture and reclaim. Additional activities and resources needed for the supply chain included in Figure 1 are aspects of waste management, energy utilization, and design concerns.

Based on our observations of a wide range of industries and arguments advanced by practitioners and the more popular business literature, we compiled a number of practical business use cases for greening supply chains. These supply chain activities and exemplary blockchain use cases and possibilities are detailed below. A summary of these use cases and possibilities appears in Figure 1 in the dashed circles.

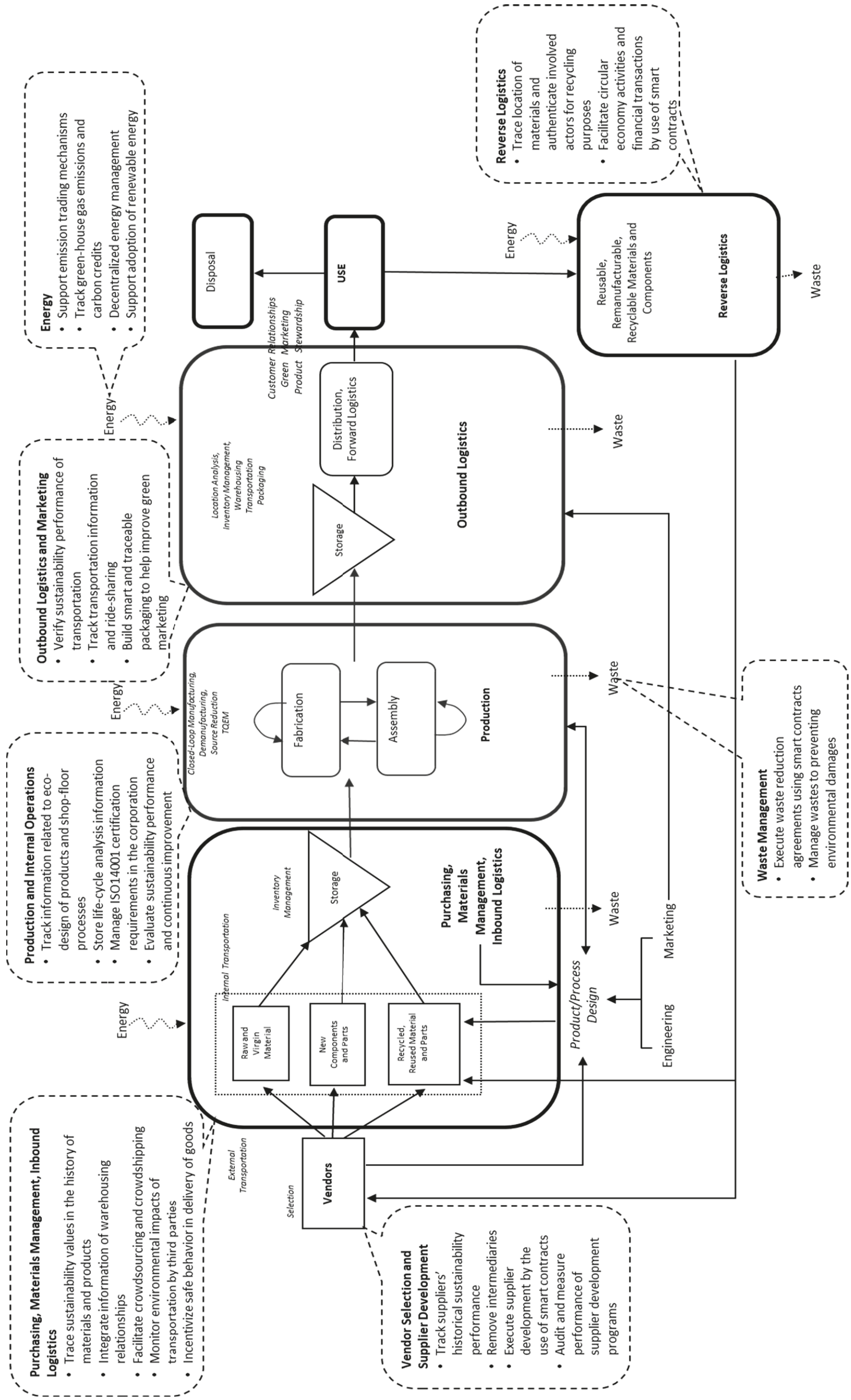

Figure 1. Blockchain application in green supply chain activities.

3.1. Vendor Selection

Supplier and vendor selection is viewed by industry and academia as a critical issue for the long-term success of supply chains. Careful selection and evaluation of suppliers are necessary initial steps to ensure the sustainability of supply chains [22]. It is this upstream portion of the supply chain that has the most profound influence on overall supply chain sustainability. Issues in the upstream supply chain can be easily hidden from buying organizations, furthering their exposure to risk and affecting supply chain resilience [23].

Supplier selection and evaluation in a sustainability context is a multi-dimensional and complex problem [24]. Usually, supplier selection and evaluation is dependent on information. This information is not easily accessible, certifiable, and audited, especially in non-economic, social and environmental, sustainability dimensions [25]. It is this major sustainable information limitation barrier that can be effectively alleviated using blockchain technology.

Vendor historical performance and sustainability data can be made available on the blockchain. This accurate and secure data about vendors' environmental performance help companies to improve their vendor selection processes based on green performance values. Using blockchain not only facilitates the vendor selection processes, but provides information regarding the whole supply chain across multiple tiers and sub-suppliers [26]. The shared information on the blockchain provides companies the opportunity to help their suppliers in selecting their vendors in different tiers of the supply chain. This would help reduce the risk for the focal companies. Removing intermediaries is also an important outcome that enhances the vendor selection process in the supply chain and reduces costs.

Current supply chain sustainability database systems exist such as the Business Social Compliance Initiative (BSCI) database for voluntary supplier social and environmental auditing in the textile supply chain [27]. These databases are available, in some form, to BSCI participants. One of the limitations of BSCI, as with other voluntary databases, is the validity and credibility of their data and audits. Blockchain technology and processes can help address some of these credibility and validity concerns and potentially satisfy third-party and non-governmental organizations (NGOs). These databases may be used for supplier monitoring, development, and selection; their credibility and accessibility can only further support these initiatives.

3.2. Supplier Development

Blockchain technology can help improve supplier development programs. The amount of investment in a supplier development program can be recorded on the blockchain platform. The type of knowledge that is exchanged and the type of organizational support has been given to the suppliers are traceable through the smart contract. The recorded information provides the basis for performance measurement of supplier development programs. Comparison between the performance before and after implementing a training program is possible on the blockchain. By means of smart contract, companies can ensure that they trade with suppliers that are involved in supplier development programs. This can also be a principle for selecting suppliers.

Environmental performance measurement and benchmarking systems will be valuable in determining potentially problematic suppliers within the supply chain. There will be issues of direct green supplier and sub-supplier development concerns. It is these traditionally invisible entities in the supply chain that can be the most environmentally risky and poorly performing members of the supply chain. Visibility further down the supply chain can more effectively identify potential sub-suppliers that may require green development and support [26].

Organizations such as Dell, IBM, Lucent, and Pepsico have extensive environmental supplier development and training programs [28]. These organizations need to record and monitor suppliers included in their programs, which can number in the thousands of suppliers. Documenting and monitoring these suppliers also allows them to build their supplier capabilities and share them with a broader set of customers. That is, not only will the direct suppliers such as Dell, IBM and Lucent have knowledge of their green development, but other customers can potentially have access through industry associations such as the Electronic Industry Citizenship Coalition (EICC).

3.3. Purchasing

Instead of supplier data, product and material data and movement can be maintained on the blockchain. Every product can have several transactional characteristics that are recorded on the blockchain, along with the historical data of a product. These transactions may declare the origin of the product, the quality, quantity, owners, and time. These data provide the ability to trace green quality, recyclability, and carbon footprints. The environmental information ensures customers are aware of safe and sustainable production and transportation of goods. Therefore, customers, with the ability to access this information, would have the opportunity to select sustainable products [29].

To ensure sustainable purchasing, companies can track the journey of resources for rare and high value products. The ability to track the source of products to address biodiversity concerns and contribution of products to resource depletion are two cases that demonstrate the role of blockchains in ensuring the sustainability of products. Using blockchain technology, life-cycle analysis of products can be completed using actual product data, rather than by estimating the values, such as in current life cycle analysis methods, as demonstrated by Favi et al. [30]. This accurate and actual information is a revolutionary contribution of blockchain technology in the life-cycle analysis domain.

3.4. Materials Management and Inbound Logistics

The location and type of facilities, and design of logistics networks to ensure sustainability can be supported with blockchain data. One particular issue is inventory management in a supply chain through warehousing. A significant amount of warehousing is outsourced to third-party logistics providers. Currently, disparate information systems are used to manage these warehousing relationships. Reduction of auditing and compliance for 'bonded warehouses', as well as tracing products and materials can all be supported through blockchains. Cross-border trade will be influenced from a tracking, finance, and scheduling perspective.

In these cases, traceability and auditing increase the sustainability of the warehouse operations by lessening waste due to product and materials loss. Also, scheduling and planning can be more effective by having utilization information for a network of warehousing choices. Alternatively, the increased use of blockchain in these settings, as in all settings, requires additional energy usage.

Another emergent warehousing and logistics issue is crowdsourcing. Crowdsourcing is an outsourcing strategy that places an open invitation to a broad group of participants to perform a task. This approach is similar to the sharing economy situation someone who has available capacity for storage or delivery can respond to these requests. FLEXE is a company that allows anyone with temporary warehouse capacity to sell it to those that need the space. Companies such as Rideship, Zipmets, and Deliv all provide services for crowdshipping. This crowdshipping takes advantage of nearby delivery services with the ability to service local needs. It also reduces the need to build additional warehousing and vehicles, and increases efficiencies associated with consolidation of materials. All these are win-win, joint environmental and economic benefits, providing opportunities for logistics providers.

A difficulty of these current sharing systems are transaction costs, with most of the benefits accrued by the service providers. The more democratic blockchain systems allow for a broader set of participants, potentially aiding, from a social sustainability perspective, lower income regions and individuals. There are current concerns with the use of blockchain crowdsourcing-related malicious agents in all areas of blockchain processing and activities (see [31]). In addition, there are more secured payment possibilities through the use of cryptocurrencies and tokens, which are pervasive due to blockchain technology.

Transportation between and among facilities is central to both outbound and inbound logistics. When contracting with a third-party transportation company, tracing and monitoring transportation will benefit from blockchain technology [29,32]. Transportation causes significant environmental damage and is one of the highest emitters of greenhouse gas emissions, local air pollutants causing smog, and contributes to depletion of energy resources. On the in-bound side, tracing the performance of transport vehicles, as with truckers for example, uses electronic logging devices. Fraudulent actions can occur in the truckers' logs that owners may ignore for purposes of expediency. Some of these behaviors may cause environmental damage, such as driving faster increases emissions and fuel usage.

Changing driver behavior is an important way to save energy resources and improve safe driving. Utilizing cryptocurrency tokens could effectively reward drivers for safe and green practices; these practices may be monitored using blockchain technology with mobile technology. Most current incentive systems are tasked with delivering products quickly and only being rewarded when driving certain distances. These current incentives cause dangerous and unsustainable practices, such as drivers speeding more often and driving longer than allocated hours, creating dangerous conditions.

Building trust in the technology, its broad adoption, and agreed upon industry standards are all issues facing the adoption of blockchain in transportation.

3.5. Production and Internal Operations

Production and operations are internal activities within an organization. Whether the production is based on manufacturing goods or delivering services, the transformation of inputs into outputs are central activities of the production stage. Traditional goods manufacturing includes fabricating or assembly activities. Internal production and supply chain activities require environmental management practices, including production management, environmental management systems, eco-design, performance measurement, environmental accounting, reporting, life cycle analysis, source reduction, closed loop internal systems, and a variety of similar greening practices, that fall within the purview of the focal organization.

A linkage of these green practices to external blockchain activities resulting from upstream, downstream, and closed-loop activities needs investigation and determination. Each of the practices and systems can be profoundly influenced from resources and inventory management, flow of materials across the shop floor, to eco-design of products.

The ISO 14001 standards are a popular global environmental management system (EMS) certification. EMSs are critical to internal operations environmental management. Blockchain implications relate to acquiring and maintaining certification. The use of audit teams to certify ISO 14001 organizations may be influenced by the technology. ISO 14001 is dependent on documentation for full certification. This documentation is then audited. Additionally, ISO 14001 certification can occur simultaneously for all sites of a corporation. For multinational corporations that are distributed broadly, distributed ledger and blockchain systems can prove a valuable resource for accumulating, aggregating, and certifying dispersed documentation. Auditing for initial or recertification may become more efficient, and may even not be needed, as documentation can be evaluated and updated continuously.

Within environmental management systems, there are numerous sub-systems, especially with respect to ISO 14000 certification family modules. These subsystem standards include performance measurements, life cycle analysis, climate change, eco-design, and communications. Monitoring environmental performance measurements throughout an organization and its supply chain through a distributed verifiable system provides more accurate data for environmental management purposes. Central to EMS and production systems is the concept of continuous improvement. Continuous improvement requires performance evaluation to determine if goals are being met and if improvements are occurring. Permanent, transparent, and verified performance provides a true measure of improvement. Linking performance measurement and environmental systems globally across an organization's sites helps build broader environmental continuous improvement measures.

Many other internal activities related to production and operations potentially influenced by blockchain technology relate to other supply chain activities, including eco-design, material handling and flow, and supplier management, as examples. We delve further into eco-design and LCA initiatives.

3.6. Eco-Design and LCA

Eco-design is a particularly interesting blockchain use case that can be discussed as part of the production and operations or marketing stages of the supply chain. It involves multiple supply chain partners and functions within an organization. Eco-design, with a focus on new product development with environmental criteria playing a prominent role, is influenced by a blockchain in numerous ways. The blockchain helps with easily disseminating information to multiple parties involved, gathering and verifying information, controlling the environmental quality of materials, time management for new product development projects, and coordinating participants.

In some eco-design systems, the environmental impact of materials used requires validation. In some of these cases, specific tests need to be completed. For example, in the cradle-to-cradle design model, hazardous material weighting schemes are used for various materials. This information can be easily stored and accessed by multiple partners after a verification process. This practice is quite suitable for blockchain technology, where scalability concerns related to high volumes of transactions would not be characteristic for materials verification. That is, this process requires time and a limited number of verifications will be required. Once these materials are verified, they would be available for trade and marketing.

Materials will require verification and processing. Green process design is as important in eco-design as in green materials. These green processes require verification and improvement. Internal processes, through ISO 14001 aspects, EMS management can be improved, evaluated, and validated. External processes, potentially through a supply chain blockchain linkage of environmental management systems, will also need verification. These environmentally sound manufacturing process designs and improvements can be used with sourcing, supplier development, supplier selection, and operations management activities.

Eco-design systems integrated with LCA benefit from information accuracy. LCA materials inventory and impact constantly change with many uncertainties [33,34]. Significant environmental information uncertainty exists for these systems. LCA tools may have different foundational information, different levels of granularity, missing data, and even inaccurate information. To address some of these uncertainties, various simulation tools have been proposed to complete a sensitivity analysis, as demonstrated by Mueller et al. [34]. Blockchain validity, reliability, and transparency can reduce information uncertainty, providing better modeling inputs and outputs for eco-design and LCA tools.

Information standards based on product data technology standards for LCA data have been proposed [35]. Expanding these arguments to blockchain, as an information delivery vehicle with appropriate models developed, is natural. The same benefits derived from using these industry standards and protocols occur through blockchain technology and systems, especially with an overall goal of reducing LCA information uncertainty. Benefits for blockchain adoption for these design systems include: less time for LCA data collection; improved data quality; traceability of the data source; using actual data from suppliers, not from a generic source; and storing environmental information of a product through the end of life to better manage its recycling and disposal [18,36].

3.7. Outbound Logistics and Marketing

Downstream green supply chain activities include distribution and various customer management activities such as green marketing and packaging. Transportation, similar to inbound logistics, is a large concern for distribution channels. Distribution transportation planning is typically planned by the organization's outbound logistics systems. This may or may not include third-party logistics providers. As mentioned in inbound logistics planning, certification and verification of environmental and social performance concerns exist in this activity; blockchain processes can address these issues. Information sharing on blockchain technology reduces the required paperwork, supporting validation requirements, and prevents data manipulation and counterfeiting within logistics and transportation processes [29].

Similar to the blockchain contributing to the sharing economy associated with crowdsourcing warehousing, which applies to outbound logistics, there are transportation ride sharing activities for commercial transportation. Whether it is rail, trucking, or even light vehicles, the "Uberization" of commercial transportation is also occurring. In these cases, excess freight vehicle capacity can be managed through blockchain activities including authentication of drivers and vehicles to payment through tokens. Ridesharing achieves efficiencies in utilization of vehicles, lessening waste. Authentication of green practices and vehicles increase transparency to customers of transportation sharing.

Packaging can be reused and traced; in this example, blockchain traceability can extend the packaging material life through more efficient management. Recyclable packaging can be monitored and managed more effectively as well. With this monitoring, further confirmation of socially responsible packaging can occur. In an application released by the U.S. Patent and Trademark Office (USPTO), Walmart describes a "smart package" that would include a device that would record information on a blockchain regarding the contents of the package, its environmental conditions, its location, and more. Additionally, multinational supermarket chain Carrefour is already using a similar system where customers can scan packaging for detailed information on a product's source, production processes, and environmental characteristics.

Building packaging with blockchain information transparency can improve green marketing efforts. According to green marketing theory, consumers are more likely to purchase greener products if they are confident that the product is actually green [37,38]. This confidence increases with the transparent, verified, and immutable information from blockchains. Overall, substantial green consumer implications exist due to blockchain technology. Two examples of these blockchain activities are consumer token incentive systems to purchase green and product tracing for returning of end-of-life products by consumers. Substantial green consumer theories, including social confirmation theories to perceived behavioral control, can be used to explain the blockchain benefits for green consumer behavior and action [38].

3.8. Waste Management

Organizational waste management along the supply chain is critical to many sustainable supply chain activities. Waste minimization is the ultimate goal for organizations and supply chains. However, if waste is generated, then tracking is critical for reasons related to the circular economy and industrial symbiosis. It may also be critical from the perspective of waste disposal and potential liabilities associated with disposal.

For waste minimization purposes, smart contracts can be used to ensure waste is minimized across the supply chain. Performance criteria for suppliers for waste reduction metrics can be included in smart contract execution agreements. Metrics and management around hazardous wastes, such as those identified by the toxics releases inventory (TRI) [39], can be tracked. Specific levels may be dictated in smart contracts for acceptable performance. The waste minimization angle may be to adjust and update smart contracts as part of a continuous improvement process for supply chains. Similar to carbon trading, waste trading can also be managed.

When minimization of waste is not possible, then there are opportunities to environmentally and sustainably manage this waste. One method of accomplishing this goal is to identify how and where the waste can be used to make it a by-product or to minimize its environmental impact. Waste exchanges have been utilized for effective industrial symbiosis realization, expanding the scope from local to national levels [40]. One especially cogent application, not typically considered, is the exchange of construction waste from the construction supply chain. In the construction case, there is a strong argument for 'buildings as material banks', which can be effectively managed through blockchains and the Internet [41,42]. More on this issue in terms of traceability and verification are described in the reverse logistics discussion.

Many times, eliminating waste completely from the supply chain is impossible. When this occurs, sustainably managing the waste is required. In this situation, the waste management supply chain processes need to be managed and risk plays a significant role. Risk is especially pertinent when managing hazardous wastes, which is also an expensive undertaking. In the United States, the tracking of hazardous wastes is critical due to the long term possibility of becoming a potentially responsible party to superfund sites. This means that companies or even supply chain partners may be responsible for significant multi-million dollar cleanup costs associated with poorly managed landfills and company sites. Having a permanent record and tracking waste disposition can help manage these liability concerns. It may be valuable for government agencies for tracking responsibility of waste as well. There are a number of dimensions of waste management blockchain capabilities and limitations that have been reviewed [43]. Fraud and manipulation, wrong or loss of information, manual processing, lack of knowledge about technology, and lack of control are all concerns for waste management in this environment.

3.9. Reverse Logistics

Reverse logistics are necessary for a number of take back regulations and building remanufacturing capabilities. One of the major concerns with remanufacturing and reverse logistics planning is the uncertainty in the location and supply of material at their end-of-life. Knowing the location of a material (i.e., traceability) to be taken back or remanufactured can help reduce uncertainty in the materials. Regulatory policies, such as the waste electrical and electronic equipment (WEEE) requirements, state that original equipment manufacturers (OEMs) are responsible for their goods. Thus, traceability of materials in the supply chain, as well as authentication that the material belongs to a particular OEM, improves the efficiency of the process for managing return flows. Mandated producer responsibility through regulations is one aspect; voluntary extended producer responsibility and product takeback can benefit from transparency, traceability, and authentication.

Similarly, circular economy practices have at least four levels of value recovery including product-life extension, reuse, remanufacture, and recycling [44]. Other than tracing materials, as identified above, one aspect of the blockchain that may be important is the terms of exchange. Smart contracts may be set up where the financing of returns can be completed electronically. In this case, instead of transferring products and materials, some form of payment is required it is not possible to manage the actual finances. Payment may be based on the quality of the material, which can be traced by data, but also the history of the cost of the product or material. Together, these items can be evaluated and payment can be completed through blockchain payment systems.

The payment scheme is critical to attracting enough product or material to drive the product through the system. Some circular economy principles do not necessarily require that a product or material be at the end of its life, but that it is returned in some condition level. Having this information, such as the number of recycling cycles, or purchase date of a product, assist in determining values. Once the value is determined, the payment can be completed. The payment location may be critical as well. Since globalization of supply chains will continue, paying for the product or material, no matter where it exists, can be more easily completed using cryptocurrencies whose values can be based on local currencies. This supply chain finance application of blockchains along with transparency can enable circular economy practices.

3.10. Energy

Energy is an important resource for all supply chain activities and managing energy is central to greening a supply chain. Sustainable energy management typically has environmental relationships associated with air emissions, fuel resource usage, and issues such as biodiversity and hazardous materials emissions. The amount of energy required to run blockchain technology can become overwhelming, especially if there is a need to solve algorithms for solving hashes as part of smart contracts. It is not clear if mining will be necessary for supply chain activities and blockchains.

Distributed storage and operations will require significant energy requirements for electronic databases; as redundancies in data storage will potentially cause exponentially greater energy needs.

Energy-related blockchain activities may support supply chain sustainability. Some organizations and supply chains, in order to achieve zero greenhouse gas emissions, use carbon credit markets for carbon offsets. These markets have been controversial given the difficulties in tracing the location and validity of the offsets. Calculation and the additionality requirements have made them controversial [45]. Improving transparency and clarity of a carbon credit can be effective using blockchain technology trust mechanisms. Also, not all carbon credits are created equal. For example, a carbon offset credit generated from a solar farm in a developed country may not have the same total environmental and sustainability of a carbon offset credit from an environmentally sensitive and poorer nation. In the latter situation, there may be more environmental co-benefits such as biodiversity management and offering poverty alleviation opportunities.

Internal emissions trading mechanisms for supply chains can also be better supported through transparency and information sharing from blockchain technology. This type of trading can provide financial benefits for energy use reduction by trading credits. Part of the trading and incentive mechanisms can be financially supported through cryptocurrency exchange [46].

Another example of energy-related blockchain improvement for supply chains is related to decentralized energy management within and between supply chain partners or communities. Rooftop solar power can be more accessible and economically feasible, further supporting adoption of renewable energy. Digital wallets as rewards may be one avenue for incentivizing employees and organizations to adopt more renewable energy along the blockchain. Expanding neighborhood blockchain-enabled micro-grid trading of solar energy to the supply chain, such as that supported by LO3 Energy, can provide certifiable and greener energy.

4. Research Concerns

Blockchain is a revolutionary technology with the potential to challenge supply chain processes and thought. Some research is required to understand the barriers, enablers, and diffusion of this technology [47]. Additionally, research related to the influence of blockchain on sustainable supply chains at organizational strategic and operational levels, its supply chain, broader industry networks, and the macro-economy are all needed.

The research domain is quite broad for a technology that may prove disruptive to the status quo of practice. We will not delve deeply into each of these research questions, but only provide a general set of issues that require investigation. The research on blockchains, sustainability, and supply chains is in its infancy with the academic field fertile for sowing ideas, theories, and analysis; many of which will grow [48]. For example, Francisco and Swanson [18] developed a conceptual model that incorporates the theory of acceptance and use of technology. This framework addresses the intentions in the use of blockchain technology for supply chain transparency.

As we are in the early phases of blockchain, adoption and diffusion of the technology is a general concern. Diffusion theory and technology acceptance models may require direct and explicit accounting for multiple stakeholders in acceptance of the diffusion. Multiple agents are involved in the adoption and agreement to be involved in the technology. Sustainability has heterogeneous meanings to participants in a supply chain. This heterogeneity and the need for blockchain may either hinder or aid diffusion. It can hinder diffusion because not everyone will agree that investment in such a technology would help with sustainability. It may be an enabler, since supply chains and partners may seek greater homogeneity and standardization of sustainability. Thus, the role of sustainable supply chains and philosophies and practices can play differentiating roles. Studies on what factors and constructs play a role in barriers or enablers are required.

Company, industry, product, and competitive environment characteristics may each influence the adoption of blockchain technology for sustainable supply chains. For example, in industries with a poor reputation, there might be greater adoption of transparency-based blockchains to support sustainability in supply chains. In this situation, legitimacy building and theory help supply chain participants address reputational issues. Similar issues based on other traditional supply chain characteristics, including building trust, opportunism, and relationship management, can play a role based on the context. Revisiting the various organizational theories for green and sustainable supply chains [49] will be necessary. Competing theories or joint theoretical perspectives are required. For example, will information technology theories such as structuration and internal organizational adoption be more important than technology acceptance and diffusion theory be better predictors?

The theory and research necessarily need to be interdisciplinary and multilevel. For example, the issues of various boundaries and boundary spanning aspects of the research (see [50]) in supply chains are vague. The boundaries and constraints of green and sustainable supply chains include economic, organizational, cultural, technological and proximal boundaries. Whether these and/or other boundaries play a role and where we draw the boundary for blockchain technology and sustainable supply chains becomes a research question related to the impact, effectiveness, performance, and general capabilities.

An overarching question in each of these general research areas is whether blockchain technology is idiosyncratic, unique, disruptive, or just another incremental technology following the status quo rules. Do blockchain technology and the blockchain environment follow similar rules as other supply chain technological and process innovations? In other words, how can adopting blockchains be compared to current information technologies such as enterprise and supply chain wide resource planning systems? Additionally, how can blockchain technology be integrated into the current legacy information systems in the supply chain? The applicability of the current supply chain theories in the blockchain domain is a concern. From an epistemological perspective we are arguably at the level of idealism, where the empirics of blockchain technology have yet to become reality. There is currently much hype and hope associated with blockchain technology where its justification is based primarily on faith and it is uncertain whether this hype and hope result in true verifiable and empirical outcomes. What we have posited in this section is a rationalistic argument that theory and empirics need to be applied collaboratively to evaluate the idealistic notions of blockchain technology and sustainable supply chains conjectured in this manuscript.

5. Limitations and Conclusions

Actual and potential blockchain sustainable supply chain use cases and applications are extensive. We have only skimmed the possibilities of blockchain application depths; as new technology, knowledge, and needs arise, more use cases will follow. Significant additional possibilities exist. The hype and potential profits associated with blockchain technology provide substantial creative motivation to identify numerous future applications.

Disruptive technologies tend to follow the 'technology mudslide hypothesis' [51]. That is, coping with relentless technological change is analogous to climbing a mudslide raging down a mountain. Practitioners and researchers are scrambling to make sense of blockchain technology, where even stopping to take a breath can bury an individual or organization. Incorporating sustainability and supply chains is like adding boulders of different shapes and sizes to this proverbial technological mudslide. In this paper, we attempted provide an overview of the potential of blockchain technology in the sustainable supply chain context.

Admittedly, we have only scratched the surface of the roles that blockchain can play in sustainable supply chain management. Our primary focus was identifying potential uses across the spectrum of green supply chain management functions and activities, specifically on environmental sustainability in the supply chain. Our examination has significant extensibility to social sustainability, and some of this was made explicit in our discussion.

Given the more pragmatic perspective of this manuscript, we only briefly touched upon broader theoretical and philosophical concerns of blockchain technology in sustainable supply chains. A complete and detailed theoretical research evaluation of sustainable supply chain blockchain technology is still required, but true empirical and theoretical evaluation will mature as adoption matures. Moving beyond the hype and hope is necessary for rational determination of effectiveness.

The final thought we present is whether blockchain technology is a true disruptive social innovation, or is another affectation of incremental technology with limited strategic significance for sustainable supply chains. This question remains to be answered.

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sustainability

MDPI

Article

Rework Quantification and Influence of Rework on Duration and Cost of Equipment Development Task

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Abstract: Rework is a sub-task within equipment development tasks that is revised after initial completion to meet task requirements. Some sub-tasks require multiple rework iterations due to their uncertainty and complexity, or the technology and process needs of the overall task, resulting in inefficient task implementation and resource wastage. Therefore, studying the impact of rework iterations on the duration and cost of development tasks is worthwhile. This study divides rework into foreseeable and hidden types and uses several methods to express and quantify their parameters. The main influencing factors in rework iterations—the uncertainty and complexity of the development task—are quantitatively analyzed. Then, mathematical and mapping models of the dependence between sub-tasks, uncertainty, complexity, and rework parameters are established. The impacts of rework type and rework parameters on the duration and cost of equipment development tasks are analyzed via simulation based on the design structure matrix (DSM). Finally, an example is used to illustrate the influence of different rework types and rework parameters on development tasks' duration and cost. The results show that the duration and cost of development tasks are greater, their volatility range is wider, and the distribution is more dispersed when both foreseeable and hidden rework are considered.

Keywords: equipment development task; foreseeable rework; hidden rework; uncertainty; complexity

1. Introduction

Equipment development is the process of obtaining a combination of equipment, or equipment with a specific function, through purposeful, planned, and constantly repeated exploration, testing, demonstration, and trial production. Equipment development is the process of upgrading to promote the sustainable development of the equipment manufacturing industry. Estimating the duration, cost, and resources required for rework iterations in an equipment development task is impossible. Thus, many equipment development tasks run over schedule, incur cost overruns, and must even be suspended, resulting in a great waste of human, material, financial, and other resources. Promoting the sustainable development of the equipment manufacturing industry requires the consideration of project duration, cost, and other indicators to ensure an effective analysis, evaluation, and selection of the equipment development task plan [1]. An equipment development task requires a large investment of resources and a huge amount of work to be executed within a short timeframe [2]. Completing a development task requires cooperation between many development teams and a high degree of innovation. An equipment development task is very complicated and carries a high level of uncertainty. Due to the influence of rework, overlap, and other factors, development task duration and cost will fluctuate widely and are difficult to effectively predict, manage, or control. The uncertainty and complexity of equipment development tasks are the main factors affecting rework iterations, which occur often because of those factors [3]. In general, rework iterations have a positive effect on the successful completion of equipment development tasks, but they increase their duration and cost [4,5]. Accurately estimating duration and cost requires an accurate analysis of the uncertainty and complexity of the proposed equipment development task. We establish a quantitative relation model measuring the degrees of dependence between sub-tasks, uncertainty, complexity, and rework parameters and then analyze the influence of rework parameters on the duration and cost of an equipment development task.

Next, this article discusses the connotations, classification, and main influencing factors of equipment development task rework and analyzes methods of evaluating its main influencing factors. Then, a mathematical model and mapping model of the relationships of dependence between sub-tasks, uncertainty, complexity, and rework parameters are established. Then, a development task simulation model is established based on the DSM. Finally, an example is used to illustrate the influence of different rework types and rework parameters on the duration and cost of development tasks.

2. Literature Review

The degree of information dependence between sub-tasks is an important factor to consider in a quantification of an equipment development task. The DSM is a structured modeling tool used to represent the dependencies between elements in a domain [6,7]. The DSM describes the serial, parallel, coupled, or iterative relationships among activities from the perspective of information flow, and provides a concise and clear matrix representation for complex processes. It can be used to analyze the dependencies, rework iterations, and other issues between sub-tasks in development tasks [8]. Steward applied the DSM to the analysis and management of complex systems [9]. Since then, DSM has been widely used for the process optimization, collaborative design, and risk analysis of products [7,10]. The DSM can be used to analyze dependencies between elements in a domain, but it is necessary to analyze the dependencies of elements between different domains. Scholars have also studied mapping models of the relationships between elements in different domains and constructed domain mapping matrices (DMMs), multi-domain matrices (MDMs), and extended domain mapping matrices (EDMMs), which can be used to describe and quantify the dependencies between elements in multiple domains (such as product domain–functional domain, functional domain–organizational domain, and team–product–function relationships) [7,11].

Uncertainty is a main factor causing rework iterations in equipment development tasks and thus needs to be considered in rework quantification. The uncertainty of an equipment development task is influenced by many factors and has a wide range of causes. The potential for certain events to occur, lack of information, and ambiguity will lead to uncertainties in equipment development tasks. Planning and implementing equipment development tasks require the effective identification and management of the main influencing factors of uncertainty [12]. Uncertainty can be divided into technical, market, environmental, process, and interrelation types [13]. Uncertainty can be further divided into variation, foreseeable uncertainty, unforeseeable uncertainty, and chaos types based on its degree [14]. Jensen et al., [15] constructed a model of the relationship between projects and the environment caused by uncertainty factors, identified the main factors that cause project uncertainty, and analyzed their influence on project structure, process, and operational effect. Li et al., [16] analyzed three uncertainties: the activity, the design plan, and the environment. Their model quantitatively described the impact of these three uncertainties on rework probability in the development of new products. Yang et al., [17] used parameters such as iterative probability, iteration length, number of iterations, and learning curve to characterize the uncertainty of product development and used overlapping levels to characterize the ambiguity of product development. They built a discrete event simulation model based on Arena to simulate a research and development (R&D) project and study how uncertainty related to iteration and ambiguity related to overlaps affected product development duration.

Complexity is another main factor that causes rework iterations in equipment development tasks and that needs to be considered in rework quantification. Complexity can be of technological, organizational, content, informational, objective, or environmental kinds. The current focus of the literature's research on project complexity is organizational and technical complexity [18,19]. Baccarini [20] discussed the meaning and specific influencing factors of project complexity from the perspectives of organization, technology, and information. Lu et al., [21] examined large-scale projects with large numbers of sub-tasks and high degrees of complexity and focused on tasks and organizational perspectives to investigate a complexity measurement model that considered hidden workloads. The Shanghai World Expo construction project was selected as a case study with which to verify the effectiveness of the proposed method. Many scholars have studied the complexity evaluation of R&D tasks from various perspectives and using various methods, but no uniform method of evaluating the complexity of R&D tasks has yet been established. Bosch-Rekveldt et al., [22] proposed a complexity measurement model for the development phase of engineering projects. Large-scale engineering products and equipment are very complex and generally have a long R&D cycle. Design changes often occur in the R&D process, which can result in schedule or cost overruns. Rebentisch et al., [23] evaluated the impact of changes in the technical systems of R&D projects as well as their impact on costs and duration based on structural complexity.

Development task simulation based on DSM is an important method of analyzing the operation effect of a development task. Many scholars have carried out extensive research on this problem. Browning et al., [24] built the first DSM-based product development process architecture simulation model, which laid the foundation for DSM-based R&D task simulation. The model allows us to consider factors such as rework iteration and learning effect and to estimate the duration of R&D projects based on discrete event simulation [25]. Large amounts of resources are required in the implementation of equipment development tasks. Cho et al., [26] conducted project simulations under resource-constrained conditions based on the DSM. Many factors influence the development of equipment, and most are uncertain. Zhang et al., [27] constructed a simulation model of development tasks under the influence of multiple uncertain conditions. Luo [28] evaluated the impact of product architecture on evolvability using simulation methods. Karniel et al., [29] constructed a DSM that reflects changes in the product development process and proposed a product development process management method based on multi-level modeling and simulation. The influence of rework iteration and change propagation on the product design process can be analyzed when a product development process changes based on a discrete event simulation model [30].

Much fruitful research has been conducted on rework quantization, uncertainty, complexity, and simulation in development tasks. For the quantification of rework parameters, the degrees of information dependence between sub-tasks are used to quantify the foreseeable rework parameters. Little research has been conducted on the influence of uncertainty and complexity on the rework parameters of equipment development tasks. Studies on how development task rework affects schedules and costs have considered only foreseeable rework, assuming that the rework probability is known, and the impact of hidden rework has not been considered. Equipment development tasks have many influencing factors, large uncertainties, and complex network structures. It is difficult to estimate the workload needed for rework, and its duration and costs fluctuate widely. To better evaluate, manage, and control equipment development tasks, it is necessary to further study the impact of sub-task rework on the duration and cost of equipment development tasks based on a classification of the influencing factors and quantitative methods of rework.

3. Connotation and Main Influencing Factors of Equipment Development Task Rework

3.1. Connotation and Classification of Rework

Rework is a sub-task within equipment development tasks that revises, improves, or perfects after initial completion to meet the requirements of the equipment development task. This occurs due to the coupling between sub-tasks, information changes, and errors during sub-task execution. The probability and impact of rework in some sub-tasks are foreseeable, although some sub-task rework may be random and difficult to anticipate. For this reason, the rework of sub-tasks in equipment development tasks can be divided into foreseeable and hidden rework tasks.

Foreseeable rework is caused by certain specific factors, such as sub-task coupling and information dependence. It can be predicted at the equipment development task planning stage, and the probability of occurrence and impact can be estimated. In the equipment development task planning stage, the foreseeable rework parameters are generally predictable, including the rework sub-tasks and sub-tasks that triggered the sub-task rework, the probability of rework occurrence, and the rework impact.

Hidden rework is caused by random factors such as mistakes in the development process and changes in requirements. This type of rework occurs randomly and cannot be predicted during the equipment development task planning stage. Sub-tasks with hidden rework, sub-tasks that cause hidden rework, hidden rework probability, and hidden rework impacts are all randomly generated.

3.2. Main Factors Affecting Rework

Many factors can affect the redevelopment of the equipment development task. The main ones are the development task's uncertainty and complexity.

3.2.1. Uncertainty

Uncertainty is the state in which people cannot, or do not, accurately grasp the full impact of future activities or events. It reflects a gap between objective reality and people's subjective knowledge [31].

Because of the complexity and uniqueness of each equipment development task, each task is different, and there is little historical experience or information that can be used for reference, making development tasks highly uncertain. The uncertainty of the equipment development task is affected by many factors, including market uncertainty, technical uncertainty, environmental uncertainty, and the uncertainty of the interrelationship between participating parties [13], as detailed below.

(1) Market uncertainty: Equipment development task participants may not have an accurate understanding of the actual market demand. A deep understanding of the development task and its market demand leads to continuous revisions of market demand estimates during the implementation of the equipment development task.

(2) Technical uncertainty: We need new technological breakthroughs in equipment development tasks. However, the application of new technologies or breakthroughs in new technologies is subject to considerable uncertainty and can lead to technological uncertainties in equipment development tasks.

(3) Environmental uncertainty: Environmental uncertainty is caused by incomplete knowledge of the environment, especially the external environment, in which equipment development tasks occur [32,33].

(4) Uncertainties in the interrelationship between participating parties: Equipment development tasks require the collaboration of many participating parties. There are uncertainties in their relationships.

(5) Uncertainties caused by human factors: Uncertainty caused by human factors comprises uncertainty due to limited human capabilities, subjective prejudices, and even work negligence.

(6) Estimated uncertainty: Any equipment development task will involve the estimation of costs, duration, and quality, and such estimated data involve uncertainties [12].

The degree of sub-task uncertainty can be calculated based on the factors affecting it. The values for each factor are divided into 10 levels according to their characteristics. The larger the value, the higher the degree of sub-task uncertainty. The degree of uncertainty is calculated according to scores given by experts. The formula is

$$Uncertainty_i = \frac{\sum\limits_{j=1}^{m} \omega_j x_{ij}}{m \times 10} \tag{1}$$

where $Uncertainty_i$ is the degree of uncertainty of sub-task i; x_{ij} is the score of the influencing factor j of sub-task i; ω_j is the weight of the influencing factor j; and m is the number of influencing factors.

3.2.2. Complexity

Complexity is another important factor in the rework of an equipment development task [19]. Complexity in an equipment development task consists of the sum of the complexity of the various sub-tasks and their interrelationships. The complexity of each sub-task consists of the complexity of the internal elements of the sub-task and the interrelationships among them. The influencing factors of the complexity of the equipment development task include technical, organizational, and environmental complexity, as well as information complexity, the complexity of the objectives, and the number of sub-tasks.

(1) Technical complexity: The complexity of a technology can be described by considering the integration of the technical components and technological innovation. In general, the higher the degree of integration and innovation, the higher is the complexity of the technology.
(2) Organizational complexity: Baccarin claims that organizational complexity originates from the difference and interdependence between units within an organization [20]. Organizational differences include horizontal, vertical, and spatial distribution differences.
(3) Number of sub-tasks: An equipment development task is a systematic project. A complete implementation process requires the coordination of various sub-tasks, resources, and other elements. The number of sub-tasks will directly affect the level of difficulty involved in coordinating the equipment development task.
(4) Complexity of sub-tasks: An equipment development task consists of many sub-tasks. In general, the more complex the sub-tasks, the more complex is the overall equipment development task.
(5) Information complexity: The information required for equipment development tasks includes both internal and external information. Internal information consists mainly of input from participating units, users, suppliers, and other divisions or departments. External information mainly consists of information acquired from government policies, the economic environment, and market conditions.
(6) Target complexity: An equipment development task must achieve not only targets such as duration, cost, and quality on a management level but also technical, economic, and security goals at the functional level, while also meeting the goals of national/regional economic development, social stability, and national defense security. Thus, development tasks have a diversity of goals, which are both interrelated and interactive.

The degree of complexity of a sub-task can be calculated using a method similar to that used to measure the degree of uncertainty. The formula is

$$Complexity_i = \frac{\sum\limits_{k=1}^{n} \mu_k y_{ik}}{n \times 10} \tag{2}$$

where $Complexity_i$ is the degree of complexity of sub-task i; y_{ij} is the score of the influencing factor k of sub-task i; μ_k is the weight of the influencing factor k; and n is the number of influencing factors.

4. Confirmation of Rework Parameters and Development Task Simulation

This chapter introduces the representation and determination methods of rework parameters and the simulation process for development tasks. A list of the abbreviations used in this chapter is provided in Table 1.

Table 1. Summary table of abbreviations used in this chapter

Abbreviation	Explanation
DSM	design structure matrix
FRP	foreseeable rework probability
FRI	foreseeable rework impact
PHR	proportion of sub-tasks that may contain hidden rework
HRP	hidden rework probability
HRI	hidden rework impact
ARP	actual rework probability
ARI	actual rework impact
EMDM	extended multi-domain matrix
F_DSM	function design structure matrix
C_DSM	component design structure matrix
O_DSM	organization design structure matrix
EDMM	extended domain mapping matrix
FEL	future event list
WL	wait list

4.1. Representation of Rework Parameters

4.1.1. Representation of Foreseeable Rework Parameters

The interrelationships and rework parameters between sub-tasks of an equipment development task can be represented using the DSM. The elements of the DSM indicate that the corresponding task column of the element supplies or supports information for the corresponding row task. Given the development tasks of the n sub-tasks $T_i(i = 1, 2, 3, \cdots, n)$, element A_{ij} in the matrix indicates that sub-task T_j provides information to sub-task T_i. The values of the DSM elements that contain predictable rework information are defined as follows: $DSM_{ij} = 0$ indicates that there is no immediate predecessor or successor relationship between sub-task *i* and sub-task *j*; $DSM_{ij} = 1$ indicates that sub-task *i* is the immediate successor of sub-task *i*; and $DSM_{ij} = p, p \in (0, 1)$ indicates that sub-task *i* and sub-task *j* overlap with probability p.

The foreseeable rework probability (FRP) matrix describes the uncertainty of rework iterations and is represented by a certain rework probability. The element FRP_{ij} of the FRP matrix represents the probability that sub-task *j* will trigger the foreseeable rework of sub-task *i*.

The foreseeable rework impact (FRI) matrix denotes the impact of rework sub-tasks when predictable rework occurs. The element FRI_{ij} of the FRI matrix represents the proportion of the duration and cost of the foreseeable rework of sub-task *i* against its original duration and cost estimate, in cases when foreseeable rework is generated by sub-task *j* for sub-task *i*.

4.1.2. Representation of Hidden Rework Parameters

The hidden rework DSM is similar to the foreseeable rework DSM, but hidden rework is unforeseeable during the equipment development task planning stage, and it is not possible to determine which sub-tasks may incur hidden rework. We can use random methods to select the proportion of sub-tasks that may contain hidden rework (PHR) and the sub-tasks that will be reworked. On this basis, parameters such as hidden rework probability (HRP) and hidden rework impact (HRI) are generated randomly. The impact of hidden rework on equipment development tasks can be simulated through the DSM-based development task simulation. In the upper triangular matrix of the DSM, if an element's column may cause a rework of the element's row, the element is taken as 1;

otherwise, the element is taken as 0. The HRP and HRI are determined by a certain range of random numbers and distribution functions, respectively. Hidden rework parameters randomly generate a pseudo code, as shown in Figure 1.

```
for i = 1: n
    for j = 1: n
        if  rand > PHR
            HDSM_ij = 0   % Sub-task j does not trigger rework of sub-task i
            HRP_ij = 0
            HRI_ij = 0
        else
            HDSM_ij = 1   % Sub-task j may trigger rework of sub-task i
            HRP_ij = rand * HRPM_ij     % HRPM_ij is the upper limit of HRP_ij
            HRI_ij = rand * HRIM_ij     % HRIM_ij is the upper limit of HRI_ij
        end if
    end for
end for
```

Figure 1. Hidden rework parameters randomly generated pseudo code.

4.1.3. Representation of Actual Rework Parameters

Rework in the task-development process comprises two parts: foreseeable rework and hidden rework. Actual rework probability (ARP) includes FRP and HRP. Actual rework impact (ARI) includes FRI and HRI.

Assuming that FRP and HRP are independent of each other, ARP can be expressed as

$$ARP_{ij} = FRP_{ij} \cup HRP_{ij} = 1 - \left(1 - FRP_{ij}\right) \times \left(1 - HRP_{ij}\right) \tag{3}$$

where ARP_{ij} is the ARP of sub-task j trigger rework of sub-task i; FRP_{ij} is the FRP of sub-task j trigger rework of sub-task i; and HRP_{ij} is the HRP of sub-task j trigger rework of sub-task i.

Assuming that FRI and HRI are independent of each other, ARI can be expressed as

$$ARI_{ij} = FRI_{ij} \cup HRI_{ij} = 1 - \left(1 - FRI_{ij}\right) \times \left(1 - HRI_{ij}\right) \tag{4}$$

where ARI_{ij} is the ARI of sub-task j trigger rework of sub-task i; FRI_{ij} is the FRI of sub-task j trigger rework of sub-task i; and HRI_{ij} is the HRI of sub-task j trigger rework of sub-task i.

4.2. Determination of Rework Parameters

The equipment development task is a complex system. Its execution involves a certain degree of uncertainty and ambiguity [17]. Complexity and uncertainty are the main influencing factors in the rework of sub-tasks. Rework probability and rework impact are related to the complexity and uncertainty of the development task. The relationship between complexity, uncertainty, and rework probability is shown in Figure 2. In general, the higher the complexity of an equipment development task, the greater are the HRP and HRI. The greater the uncertainty, the greater are the FRP and FRI.

To quantify the rework parameters, we first analyze the main influencing factors in the complexity and uncertainty of the equipment development task. Complexity and uncertainty are evaluated, and the quantified values of the complexity and uncertainty levels of each sub-task are obtained.

Then, an extended multi-domain matrix (EMDM) is constructed; this is the "sub-task–component–function" EMDM, as shown in Figure 3a. EMDM can reflect the dependencies between components, functions, and corresponding sub-tasks. The function design structure matrix (F_DSM) reflects the interaction between functions. The component design structure matrix (C_DSM) reflects the input/output dependence of the key performance parameters between components. The extended domain mapping matrix (EDMM) reflects the dependencies between components, functions, and corresponding sub-tasks, that is, the dependencies of sub-tasks in implementing component related functions. The level of information dependence in the organization design structure matrix (O_DSM) can be derived by EMDM, as shown in Figure 3b. On this basis, O_DSM is normalized.

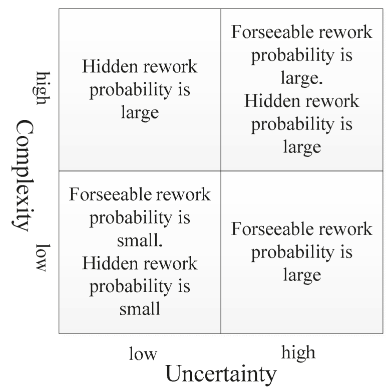

Figure 2. Relationship between rework probability and complexity and uncertainty.

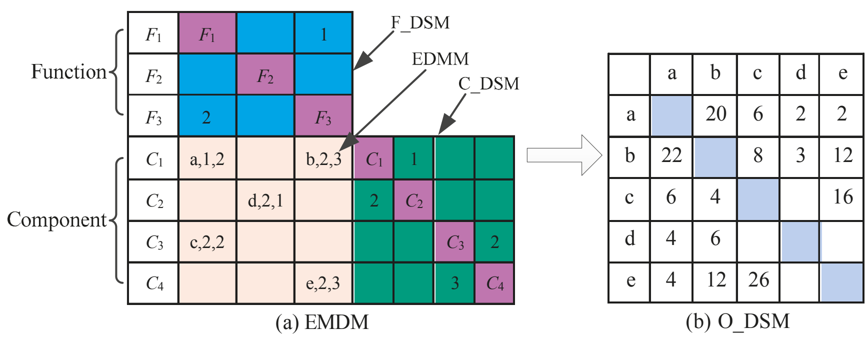

Figure 3. Organization design structure matrix (O_DSM) derivation process.

Finally, according to the degree of information dependency between sub-tasks, the FRP between sub-tasks is calculated by combining the degree of complexity and uncertainty of the sub-tasks that cause rework with the degree of complexity and uncertainty of the reworked sub-tasks. The formula is

$$FRP_{ij} = K \times \left[O\_DSM_{ij} \times \left(Uncertainty_i \times Complexity_i \times Uncertainty_j \times Complexity_j \right)^{\frac{1}{2}} \right]^{\frac{1}{3}} \quad (5)$$

where FRP_{ij} is the FRP of sub-task j trigger rework of sub-task i; O_DSM_{ij} is the normalized information dependence of sub-task i on sub-task j; $Uncertainty_i$ is the degree of uncertainty of sub-task i; $Complexity_i$ is the degree of complexity of sub-task i; $Uncertainty_j$ is the degree of uncertainty of sub-task j that causes rework; $Complexity_j$ is the degree of complexity of sub-task j that causes rework; and K is the adjustment factor.

The range of each hidden rework parameter can be obtained by mapping the complexity and uncertainty of the equipment development task to each hidden rework parameter. On this basis, each hidden rework parameter can be generated randomly.

4.3. Development Task Simulation

Development task simulation is an effective tool for analyzing the rework iterations during complex dynamic development tasks, as well as analyzing and evaluating the performance of the equipment development task through simulation data [17]. Because equipment development is highly complex and implies many uncertainties, it is difficult to analyze development tasks through mathematical modeling. Simulation tasks can be mimicked by discrete event simulation modeling [27]. A single simulation run flow diagram is shown in Figure 4. The future event table (FEL) is composed of the completion events for sub-tasks in order of the events; each element in the FEL represents a sub-task. When the FEL is not empty, this indicates that there are sub-tasks in the system that are executing. First, the first event is taken from the FEL, indicating that the sub-task corresponding to the event is completed, and the sub-task is deleted from the FEL. Then, it is determined whether the subsequent sub-tasks can be executed. The sub-tasks that can be executed are entered into the wait list (WL), and the sub-tasks in the WL are prioritized. Finally, it is determined which sub-tasks can enter the FEL according to resource constraints. When the FEL is empty, this indicates that all activities have been performed, and the simulation is over.

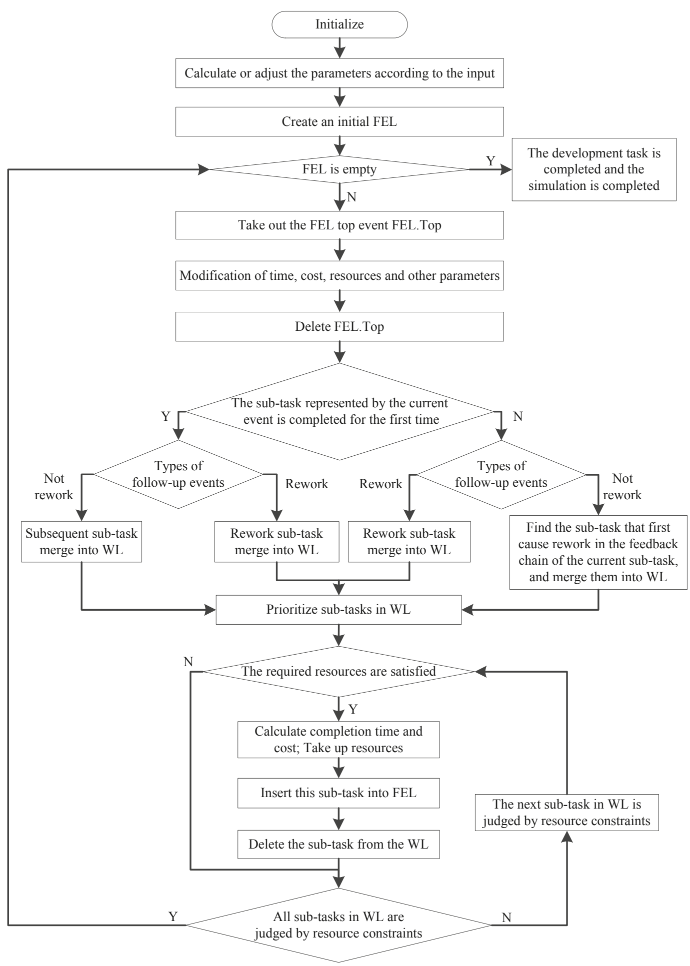

Figure 4. Single simulation operation flow chart.

Simulation allows the influence of the uncertainty and complexity of development tasks on the duration and cost of development tasks to be analyzed more intuitively and effectively [24,26]. The required input for the development task simulation model is the sub-task time, cost, required resources, DSM, FRP, FRI, HRP, and HRI. To establish the change of the trigger state of a sub-task at a given time point, the state includes the completion of each sub-task, execution, queuing, and so on.

5. Case Study on the Influence of Rework

5.1. Description of the Case Study

The development task of an uninhabited aerial vehicle (UAV) that includes 14 sub-tasks is used to conduct a case study. The duration and cost data of each sub-task are shown in Table 2. It is assumed that the duration and cost of each sub-task obey the triangular distribution. During each simulation run, the Monte Carlo method is used to extract the duration and cost of each sub-task. When calculating the rework parameters, O_DSM is derived according to EMDM and is normalized; then, the uncertainty degree and complexity degree of each sub-task are quantified according to the uncertainty influence factors and the complexity influence factors. Based on this, the PRP and PRI are calculated. If the effect of hidden rework is not considered, the DSM of the UAV development task is shown in Figure 5, and the FRP and FRI matrix are shown in Figure 6. When both foreseeable and hidden rework are considered, since the parameters of hidden rework cannot be predicted, the range of the hidden rework parameters can be set according to the degree of the uncertainty and complexity of the development task. In the corresponding value interval, parameters such as PHR, HRP, and HRI are generated randomly.

Table 2. The duration and cost data of each sub-task.

ID	Sub-Task Name	Duration (Days)			Cost (US$k)		
		D_o	D_m	D_p	C_o	C_m	C_p
1	Prepare Preliminary DR&O	1.9	2	3	8.6	9	13.5
2	Create Preliminary Design Configuration	4.75	5	8.75	5.3	5.63	9.84
3	Prepare Surfaced Models & Internal Drawings	2.66	2.8	4.2	3	3.15	4.73
4	Perform Aerodynamics Analyses & Evaluation	9	10	12.5	6.8	7.5	9.38
5	Create Initial Structural Geometry	14.3	15	26.3	128	135	236
6	Prepare Structural & Notes for FEM	9	10	11	10	11.3	12.4
7	Develop Freebody Diagrams & Applied Loads	7.2	8	10	11	12	15
8	Perform Weights & Inertia Analysis	4.75	5	8.75	8.9	9.38	16.4
9	Perform S&C Analyses & Evaluation	18	20	22	20	22.5	24.8
10	Develop Freebody Diagram & Applied Loads	9.5	10	17.5	21	22.5	39.4
11	Establish Internal Load Distributions	14.3	15	26.3	21	22.5	39.4
12	Evaluate Structural Strength, Stiffness, & Life	13.5	15	18.8	41	45	56.3
13	Preliminary Manufacturing Planning & Analyses	30	32.5	36	214	232	257
14	Prepare UAV Proposal	4.5	5	6.25	20	22.5	28.1

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	1								1					
3		1		1										
4	1		1											
5	1		1			1		1				.8	1	
6	1				.8									
7	1					.8								
8						1						1		
9	1		1	1				1						
10				1		1	1	1			1			
11						1	1	1		.9				
12	1					1	1			.9	.6			
13	1				1							1		
14	1	1	1	1	1	1	1	1	1	1	1	1	1	

Figure 5. Design structure matrix (DSM) of the development task.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	.4/.5								.2/.1					
3		.5/.3		.4/.5										
4	.3/.4		.5/.8											
5	.4/.1		.5/.1			.1/.1		.1/.1				.3/.3	.1/.1	
6	.1/.1				.4/.3									
7	.4/.5					.4/.8								
8						.5/.5						.5/.5		
9	.4/.3		.5/.3	.5/.3				.5/.3						
10				.1/.1		.5/.5	.2/.4	.1/.3			.4/.3			
11						.5/.5	.5/.5	.5/.3		.5/.3				
12	.4/.5					.4/.3	.5/.5			.5/.5	.4/.5			
13	.5/.9				.5/.9							.4/.3		
14	.3/.5	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	

Figure 6. Foreseeable rework probability (FRP) and foreseeable rework impact (FRI) matrix.

5.2. Effect of Rework Type on Duration and Cost

The analysis of the impact of rework on the duration and cost of the equipment development task is divided into two kinds of situations: those considering only the impact of foreseeable rework and those considering the effects of both foreseeable and hidden rework.

When only the impact of foreseeable rework on the duration and cost of the development task is considered, the rework parameters include the DSM, the FRP, and the FRI. At this time, parameters such as FRP and FRI are taken as constant values. When the effects of foreseeable rework and hidden rework on the duration and cost of the development task are considered, the rework parameters include the DSM, FRP matrix, FRI matrix, PHR matrix, HRP matrix, and HRI matrix. At this point, the foreseeable rework parameters are the same as in the previous case, and the hidden rework parameters are randomly generated.

When taking a specific random generation range for hidden rework parameters such as PHR, HRP, and HRI, the duration and cost are obtained through development task simulation. Then, the duration and cost are compared without considering hidden rework. The parameters of the hidden rework are as follows: the upper limit of PHR is 0.2, the upper limit of HRP is 0.2, and the upper limit of HRI is 0.2. We generated 5000 simulations for development tasks when considering only the foreseeable rework (without considering the hidden rework) and for comprehensively considering the foreseeable and hidden rework. The frequency histogram of the duration and cost of the development task for both cases is shown in Figure 7. In Figure 7a, the blue histogram represents the distribution of the development task duration without considering the hidden rework, and the red histogram represents the distribution of the development task duration when considering the hidden rework. In Figure 7b, the blue histogram represents the distribution of the development task cost without considering the hidden rework, and the red histogram represents the distribution of the development task cost when considering the hidden rework. The cumulative frequency curve of the development task duration and cost in both cases is shown in Figure 8. In Figure 8a, the blue curve represents the cumulative curve of the development task duration without considering the hidden rework, and the red curve represents the cumulative curve of the development task duration when considering the hidden rework. In Figure 8b, the blue curve represents the cumulative curve of the development task cost without considering the hidden rework, and the red curve represents the cumulative curve of the development task cost when considering the hidden rework.

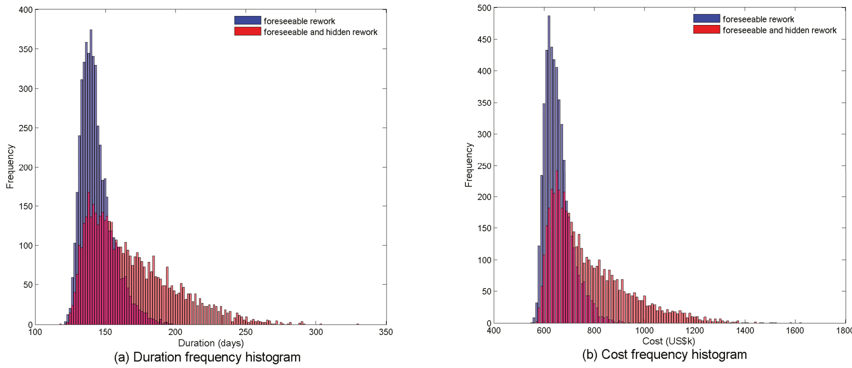

Figure 7. Duration, cost frequency histogram.

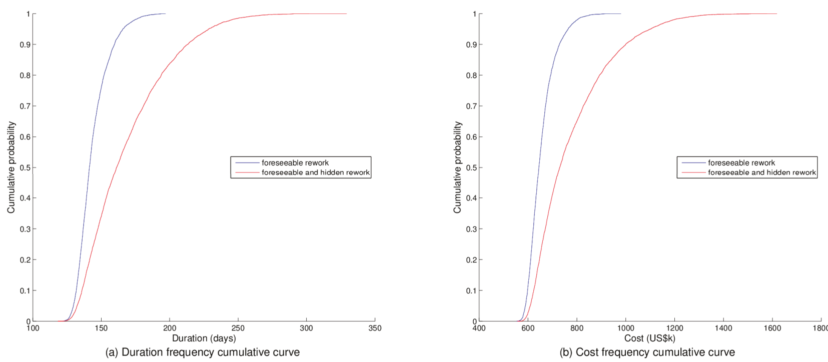

Figure 8. Duration, cost frequency cumulative curve.

The analysis shows that the average duration and cost of the development task are greater, the fluctuation range is wider, and the distribution is more dispersed when both the foreseeable rework and hidden rework are considered than when only the foreseeable rework is considered. The number of sub-tasks, ARP, ARI, and other parameters for a development task where the hidden rework effect is considered may increase because of the existence of the hidden rework. Therefore, the average duration is longer and the average cost is greater when the hidden rework effect is considered than they are when hidden rework is excluded. Since the implicit rework parameters cannot be accurately estimated, the uncertainty of parameters such as PHR, HRP, and HRI is greater. As a result, the fluctuation range of parameters such as the proportion of sub-tasks that may need rework, ARP, and ARI will increase. Therefore, when the implicit rework is not considered, the development task duration and cost fluctuation ranges are relatively small, and the distribution is relatively concentrated. When implicit rework is considered, the duration of the development task and the cost fluctuation range are relatively large, and the distribution is relatively decentralized.

5.3. Impact of Hidden Rework Parameters on Duration and Cost

To analyze the influence of different hidden rework parameters on the development schedule and cost, hidden rework parameters such as PHR, HRP, and HRI were taken from different ranges of random numbers. We compare the duration and cost of the development task under various conditions and analyze the influence of hidden rework on the duration and cost of the development task. The range of random number generation for PHR has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.4, respectively. The range of random number generation for HRP has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.5, respectively. The range of random number generation for HRI has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.9, respectively. Simulation is carried out under the conditions of the upper limit of the implicit rework parameters, and the duration and cost of the development tasks under different parameters can be obtained.

The relationships between PHR, HRP, HRI, and the equipment development task duration are shown in Figure 9 based on the simulation data. Axis *X* indicates the upper limit of HRI, axis *Y* indicates the upper limit of HRP, and axis *Z* indicates the development task duration. The four surfaces from the bottom to the top are the duration surfaces of the development task when the upper limit of PHR is 0.1, 0.2, 0.3, and 0.4, respectively. The relationships between PHR, HRP, HRI, and the equipment development task cost are shown in Figure 10. Axis *X* indicates the upper limit of HRI, axis *Y* indicates the upper limit of HRP, and axis *Z* indicates the development task cost. The four surfaces from the bottom to the top are the cost surfaces of the development task when the upper limit of PHR is 0.1, 0.2, 0.3, and 0.4, respectively.

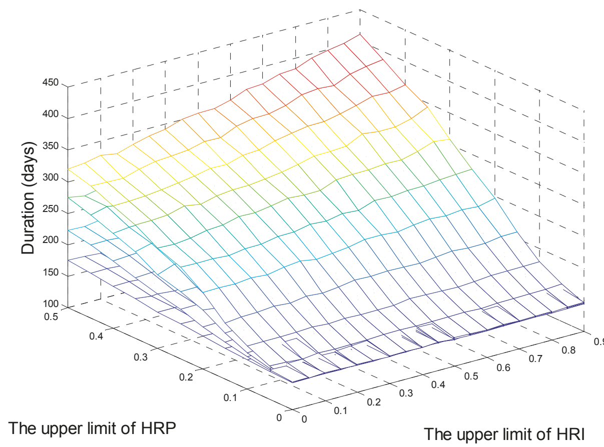

Figure 9. Relationships between rework parameters and duration.

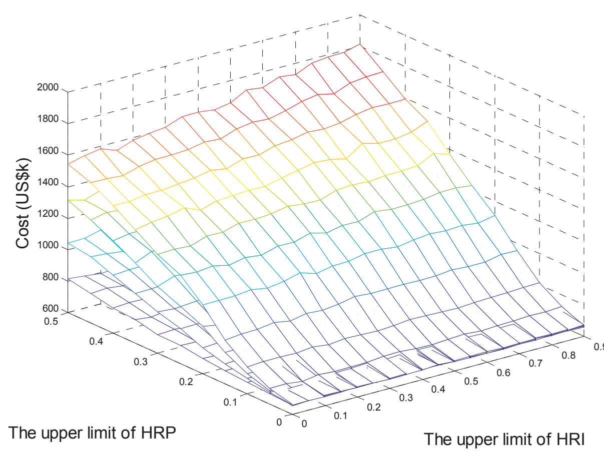

Figure 10. Relationships between rework parameters and cost.

The duration and cost of the equipment development task will increase with PHR, HRP, and HRI. Among these, PHR and HRP have a greater impact on development task duration and cost.

The relationships between equipment development duration, cost, and PHR when the upper limit of HRP is 0.2 and the upper limit of HRI is 0.2 are shown in Figure 11. As PHR increases, the number of sub-tasks occurring during the execution of an equipment development task will increase, and its duration and cost will increase. As PHR increases, the duration and cost of equipment development increase as well.

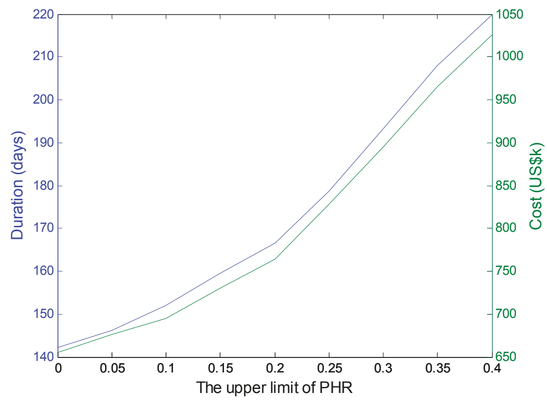

Figure 11. Relationships between duration, cost, and proportion of sub-tasks that may contain hidden rework (PHR).

During an equipment development task, ARP will increase as HRP increases. This increases the number of rework sub-tasks where rework must occur as well as the duration and cost of the overall equipment development task. The rate of increase is roughly proportional to HRP and is rapid.

When HRI increases, the number of implicit rework sub-tasks does not change, but the impact of these hidden rework sub-tasks increases, and the rework workload increases correspondingly. The duration and cost of equipment development will also increase, at a rate roughly proportional to the probability of implied rework, but it will be smaller than in the other two cases.

6. Conclusions and Outlook

This study divides rework in equipment development tasks into foreseeable and hidden types according to their characteristics, defines the concepts of foreseeable rework and hidden rework, and uses several methods to express the parameters of the two types. Unlike the traditional representation (which considers only foreseeable rework), the representation in this study can describe the actual situation of rework in a development task realistically.

This study analyzes the influencing factors of rework, establishes mapping and mathematical models of the main influencing factors in rework and rework parameters, and quantifies the rework parameters according to the model. The resulting rework parameter quantification model considers the influence of factors such as the degree of dependency between sub-tasks, uncertainty, and complexity, making it more scientific than previous models.

Based on the classification and description of rework and the quantification of rework parameters, this study quantitative analyzes the influence of rework types and parameters on the duration and cost of equipment development tasks by doing a simulation that reflects the operation effects of development tasks more accurately and analyzes the influence of rework on development tasks more deeply.

The results show that the mean duration and cost of a development task is greater, the range of volatility is wider, and the distribution is more dispersed when both foreseeable and hidden rework are considered than when only predictable rework is considered. In other words, the existence of hidden rework increases the duration and cost of a development task and widens their fluctuation range. The duration and cost of an equipment development task will increase with an increase in PHR, HRP, and HRI. Of these, PHR and HRP will have greater impacts. The PHR, HRP, and HRI parameters increase with an increase in development task uncertainty and complexity. Therefore, duration and cost will increase along with an increase in development task uncertainty and complexity.

Future studies could further explore quantitative determination methods for rework parameters. The quantification of rework parameters is an important basic factor in research on equipment development tasks. This study considers just two main factors affecting the rework of a development task—uncertainty and complexity. It is necessary to refine the factors that influence rework parameters, combine relevant theoretical analyses, mine historical data on development tasks, and construct a more effective method of quantifying rework parameters. In addition, methods of classifying development task reworking and of representing rework parameters should be explored in depth to enable the construction of a more complete description model for development task rework.

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Education and Energy Intensity: Simple Economic Modelling and Preliminary Empirical Results

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Abstract: The ratio of energy use to Gross Domestic Product (defined as energy intensity) is a major determinant of environmental hazard and an indicator of eco-efficiency. This paper explains why education can have an effect in reducing the energy intensity thus affecting eco-efficiency. We devise a stylized economic model with simple and widely accepted assumptions that highlights the role of education in decreasing energy intensity worldwide. In an empirical application that is robust to the features of the data, we show that primary schooling contributes to a decrease in energy intensity which has a very significant effect, even accounting for the other well-known determinants of energy intensity. Additionally, when schooling is taken into account, income is no longer a negative determinant of energy intensity.

Keywords: energy intensity; income; education; eco-efficiency; circular economy

JEL Classification: Q43; O17; O50

1. Introduction

The evolution of energy intensity (the ratio of energy consumption to Gross Domestic Product (GDP)—as an indicator of eco-efficiency)—across the world has been established as one of the facts that is related to energy and economics (see [1]). In fact, the energy intensity has been found to be declining in time and negatively correlated with *per capita* output. This seems to indicate that as countries get richer, energy intensity decreases. One possible explanation for this relationship is that the gains in efficiency associated with economic growth improve the way the humankind uses energy, i.e., using it more efficiently. Thus if this interpretation is accepted, the decline in energy intensity should occur simultaneous with economic growth, both as result of technological progress. Alternatively, the reduction in energy intensity has also been associated with the structural transformation of the economy. As the economy becomes more service-intensive and less industry-intensive, energy intensity tends to be reduced (see e.g., reference [2–4]). However, [5] noted that the service sector has not been very energy efficient when analyzed by a panel of countries. More recently, reference [6] pointed out the role of financial markets in the reduction of energy intensity. In particular, the author noted that energy consumption increases generally with income per capita, except for highly advanced economies with highly developed financial markets.

It is worth noting that whatever the cause that makes energy intensity decrease with economic growth, this stylized fact clearly contributes to the establishment of a circular economy, as it is a result of the introduction of more sustainable practices in societies.

Despite several attempts to include environmental education within the school syllabus since primary education (see e.g., reference [7]), the general roles of human capital, education and schooling in decreasing energy intensity have not been studied.

There have been very recent micro and case studies about environmental and climate change awareness of students in response to the environmental topics included in syllabus which is clear evidence of the rising interest of the topic. Reference [8] provides a description of the environmental education of elementary school students in Da Nang city, Vietnam and concludes, among other things, that students' environmental awareness improves after environmental education activities. Reference [9] studied students' environmental awareness in some elementary schools in Zonguldak, Turkey. Reference [10] analysed students awareness in high schools in Taiwan. In this study, generally, students were relatively familiar with topics taught in schools and had a positive attitude related to energy saving. Moreover, students with more educated parents tend to have significantly better knowledge than others. This may be an indication of the importance of home-taken practices and home education regarding environmental issues. Reference [11,12] studied the behaviour of secondary and elementary students, respectively, in Greece. Both revealed the importance of education in environmental awareness and in implementing energy saving and environmental friendly practices. Finally, reference [13] argues that schools must build upon up-to-date curricula and classroom activities based on cutting-edge knowledge on what drives human learning in order to increase students' environmental awareness. The acceptance of renewable energies by communities is a related topic, but within that topic, the importance of schooling has not been mentioned by the literature (for surveys on this literature that support this claim please see reference [14,15]). In this paper, we use the concepts of human capital, education and schooling in an inter-exchangeable manner while we recognize their different scopes and measures. While human capital includes both education and in-work experience and both can have effects in decreasing energy intensity, we really focus on the concept of education in the model, as the families choose between consumption and education (of the offsprings). Then, in the empirical application, we use schooling as it is the variable with the most available data. We leave the study of other aspects of human capital in energy intensity and eco-efficiency for further research.

We have not found studies with particular concern about the relationship between education and energy intensity at the country level. We intend to fill this gap. First, we offer an explanation based on quite intuitive and widely accepted assumptions: (i) there is a minimum subsistence level of consumption; (ii) families choose between consumption and education; and (iii) more knowledge reduces energy intensity, which can be explained both from the supply or/and the demand side of the economy.

Second, energy intensity has been analysed essentially in country or region-specific studies and with a limited data range. The methods used were almost descriptive or, at most, applied some basic econometric tools such as Ordinary Least Squares (OLS). We aim to broaden the study of the determinants of energy intensity to a large panel of data from countries, focusing on the effect of *schooling*. To that end, we include variables which were typically associated with energy intensity: income *per capita*, the industry share in the economy, energy dependence, and we also take convergence in energy intensity into account. We obtain a very strong significantly negative effect of schooling in decreasing energy intensity, supporting our presented theory. In fact, we postulate that a more educated population not only learns how to improve energy use and then to decrease its intensity in economic activities, but also becomes more aware of issues such as global warming and pollution problems and thus uses energy more efficiently. Besides that, when schooling is not taken into account, the *per capita* income has a strong negative effect but only in the short run, and external dependence has only a marginal negative effect on energy intensity, also in the short run. Thus, this is the first paper highlighting the role of education in reducing energy intensity and substituting the role of income *per capita* but maintaining the significance of all the other major determinants of energy intensity.

This paper has clear policy implications as the influence of education in energy use should be taken into account when designing education policy. Furthermore, the influence of education in energy intensity is also informative for environmental policy, as this can rely more on the educational system to achieve environmental goals.

The remainder of the paper is organized as follows. Section 2 presents a simple model that highlights why education can have a negative effect on energy intensity and thus presents education as a potential alternative determinant of the decreasing path of energy intensity. Section 3 describes the data features, the econometric specification and the methodology. This section also highlights the features of the econometric approach that deals correctly with the main data features. Section 4 presents the empirical results. In this section, we present tests of the estimation goodness-of-fit, regressions results and their analysis. Section 5 concludes the paper.

2. Why Education May Reduce Energy Intensity?

A simple application of a structural transformation model (such as the one of reference [16]) would explain the importance of de-industrialization in explaining energy intensity decline given that industry is more intensive in energy than services. Thus, an increase in services and decrease in industry in a given economy will directly determine the reduction in energy intensity. However, the role of human capital in reducing energy intensity is yet to be explained. In this section, we provide a simple explanation as to why schooling can reduce energy intensity, thus contributing indirectly to decreasing the hazard caused by energy intensity. This explanation is linked with very intuitive phenomena—families need a certain amount of consumption to survive; thus, the choice between consumption and human capital implies a higher growth rate of human capital (relatively to that of consumption). Human capital contributes to the evolution of knowledge and knowledge decreases energy intensity. Note that in aggregate terms, the growth rate of energy intensity is proportional to the growth rate of consumption minus the growth rate of human capital and, as a result of that, energy intensity declines.

2.1. A Simple Model Explanation

We devised a very simple model that shows how human capital can contribute to reducing energy efficiency and eventually to substitute the role of income, as also happens in the regressions that we show in the following section.

The agent chooses consumption and human capital, following an utility function, U, as follows:

$$U = log(c - \bar{c}) + \sigma log(h), \quad (1)$$

where c is consumption; $\bar{c}$ is the minimum level of consumption or the subsistence level of consumption (e.g., as in reference [17]; h is the level of human capital (or education) chosen by the families; and σ is the weight of human capital in the families' preferences. There are various reasons why we may include human capital (or education) in the families' utility function: (i) because it represents the human capital of the offspring, which is correlated with their future income (e.g., as in reference [18]); (ii) because it is correlated with family health (e.g., in reference [19]; or (iii) because the families value their own or the offspring's knowledge (as in references [20] and [21]. We use this latter approach which serves our goals without unnecessary technicalities. The economy's resource constraint is $y = c + h$, which assumes that all prices are constant and equal in this economy, which is also a simplification without loss of generality for our purposes.

Families or society stock of knowledge evolves with the use of human capital (or schooling), such that $A = Bh$ (in which A stands for families or society knowledge and B is a constant), which is, again, a simplification that does not imply any loss of generality for our purposes. In fact, a very fruitful body of literature beginning with reference [22] has modelled knowledge accumulation as dependent on human capital employed in the technology sector (as a supply-side explanation). However, this can alternatively be the result of a demand-side explanation. One justification for this demand-side view is that the incentives for new technologies to be invented depend inversely on the skilled workers' wages, which are negatively related to human capital (see reference [23]). The lower the wages and the higher the demand for human capital, the higher the incentive to accumulate technological knowledge is. Regarding the adoption of cleaner technologies specifically, reference [24] confirms that "customer requirements are another important source of eco-innovations, particularly with regard to products with improved environmental performance and process innovations that increase material efficiency, and reduce energy consumption, waste and the use of dangerous substances". In fact, the demand for new technologies can be seen as being dependent on the level of human capital.

Finally, energy intensity (Ei) is a function of consumption and technology, such that

$$Ei = c^{\varrho}/A, \tag{2}$$

where $0 < \varrho < 1$ represents the elasticity of energy intensity to growing *per capita* consumption to account for the fact that consumption positively influences energy intensity but at a decreasing rate. From Figure 1 in reference [25]'s report, we can infer a positive effect of the increase in *per capita* consumption on energy efficiency; thus, ϱ should be positive. However, the decreasing rate may be explained by the growing demand for energy efficiency and for "clean" electricity (see the same in Figure 1 in reference [25]). The same report highlights the importance of new technologies in the falling trend of energy efficiency. There is also literature on economic growth theory in which pollution can be decreased by technological developments ([26,27]). Reference [28] studied the importance of developing new technologies in decreasing costs and implementing more innovative and practical approaches to energy management. Additionally, reference [29] showed that the increase in energy efficiency and promotion of renewable energy consumption are the main tools to achieve the Environmental Kuznets Curve (EKC), emphasizing the negative relationship between pollution and output growth occurrence at the world level. Otherwise, the authors concluded that the relationship between greenhouse gas emissions and total production output would be monotonically positive. The EKC, which is a related concept to the relationship between energy intensity and income (but not the same), is a hump-shaped relationship between pollution and output growth that has been extensively debated in the literature—for a critical history of the concept of the EKC see, e.g., Stern (2004) [30]. An increase in families or society's stock of knowledge (including that accumulated through home or primary schooling) is important to increase energy saving awareness and can also be related to a decrease in energy intensity. This has been recognized by reference [10,31].

2.2. Solution of the Model

The agent maximization problem yields the optimal marginal rate of substitution between consumption and human capital:

$$\frac{1}{c-\bar{c}} = \frac{\sigma}{h}. \tag{3}$$

After substitution into the resource constraint, the following equations for the optimal quantities for consumption and human capital are obtained, respectively:

$$c = \frac{y+\bar{c}}{1+\sigma};\ h = \sigma\left[\frac{y+\bar{c}}{1+\sigma} - \bar{c}\right] = \sigma\left[\frac{y-\sigma\bar{c}}{1+\sigma}\right]. \tag{4}$$

From Equation (4), the relationship between the growth rates of consumption and human capital (g_x is the growth rate of variable x) with the output growth rate is given as follows:

$$g_c = g_y\frac{y}{y+\bar{c}};\ g_h = g_y\left[\frac{y}{y-\sigma\bar{c}}\right]. \tag{5}$$

The following proposition highlights the main results of this stylized model.

Proposition 1. *The growth rate of energy intensity is negative due to the influence of the human capital growth rate.*

Proof. From Equation (5), it is straightforward to obtain $g_c < g_h$. Then, Equation (2) is used to obtain $g_{ei} = \varrho g_c - g_h < 0$, given that $0 < \varrho < 1$. □

This means that a very stylized model which considers that (i) there is a minimum level of subsistence consumption; (ii) that energy intensity depends positively on consumption and negatively on knowledge (the model can encompass concepts such as cleaner technologies or families awareness); and (iii) that knowledge depend positively on education investments by families (e.g., in schooling) explains that energy intensity should decline and that this fall should depend crucially on education or schooling. While assumptions (i) and (iii) are quite common in economics literature, assumption (ii) relies on recent evidence on energy intensity trends. To sum up, in aggregate terms, the growth rate of energy intensity depends (positively) on the difference between the growth rate of consumption and the growth rate of human capital and, as a result of that, energy intensity declines.

3. Empirical Application

3.1. Variables and Sources

We used data from the Cross-National Time Series (CNTS) Data Archive (2015 edition), also known as Databanks International [32], to collect the variables for this article. The dependent variable was energy intensity (energy consumption per unit of GDP). Our variable of interest is schooling measured by the enrolment of primary schooling students as a percentage of the total population. This was chosen as it is the most general level of education and should proxy the investment that each society is making in educating its population towards environmental awareness. For the first time in the literature that aims to explain energy intensity, we considered an education variable as a possible explanatory variable.

As other explanatory control variables, we used the other determinants of energy intensity which have been mentioned in the literature. Each of them are defined below with an explanation of the reason for them to be included in our analysis:

- Income *per capita* (Gross Domestic Product *per capita* (factor cost)). We chose to use GDP *per capita* at factor costs as this excludes the influence of taxation (and subsidization) in the economy (which GDP at market prices would include). Most articles that explain energy intensity at the country level (such as reference [2,4]) use income *per capita* as an explanatory variable.
- Percentage of GDP originating in industrial activity (or industrial share in GDP). Some papers have analysed the effect of some sectors' shares in the economy (e.g., reference [4]) or an industry dummy (e.g., reference [3]) as determinants of energy intensity. To deal with this issue, reference [5] studied energy intensity only in the services sector. Although reference [2] ignored this variable, reference [33] exhaustively explored the relationship between industry share and energy intensity.
- External energy dependence (energy consumption minus energy production). This variable was introduced to proxy price shocks. Prices is also a common variable to enter in regressions in country-specific studies, as in reference [2] or [4]. However, as a substitution variable for the price of energy comparable between different countries, which we could not obtain, we used external energy dependence. As reference [34] stated, "by energy dependence, we mean the vulnerability of a given Member State to energy price shocks or energy supply disruptions".

Table 1 presents the descriptive statistics for the variables.

Table 1. Descriptive Statistics.

Variable	Observations	Mean	Std. Dev.	Min	Max
Energy Intensity	7322	0.801	1.078	0.006	17.679
GDP *per capita*	9503	4538.516	10622.56	18	186,243
Share of Industry	5393	27.556	14.160	0	96
External Energy Dependency	6949	−2980.458	63,021.74	−618,978	641,541
Primary Schooling	12,552	0.1134	0.0556	0.0001	0.4943

Notes: Energy intensity is measured as energy consumption per unit of GDP; GDP *per capita* is at factor costs (units of US dollars); the share of industry is the ratio of the industrial output to GDP; the external energy dependency is a trade balance of energy (energy consumption minus energy production); primary schooling is the enrolment of students in primary schools *per capita*. The presented statistics were calculated for the following number of observations.

3.2. Cross-Country Dependency and Non-Stationarity

The non-stationarity of macroeconomic variables is a well-known feature that has concerned macro-economists, namely after reference [35]'s contribution. More recently, reference [36], for instance, concluded that real GDP and GDP *per capita* are non-stationary. Additionally, variables linked with energy (namely energy consumption) also share the same property (see e.g., [1]). This means that an empirical approach that relates macroeconomic variables in the long-run to any other macroeconomic variable (in particular, energy intensity) must account for the potential non-stationarity of the series. Our approach is robust to the presence of non-stationarity in the series—see reference [37] for the advantages of using the common correlated heterogeneous panel data estimator to deal with the common features of macroeconomic series in large panels of data.

Additionally, income growth, energy intensity decline and structural transformation are worldwide phenomena and are obviously correlated among different countries. International technological shocks (such as the introduction of electricity or the computer on production) or financial shocks (such as the sub-prime crisis) are often considered to be the sources of cross-correlation of GDP *per capita*. We have historically observed that these shocks are contagious to various neighbour countries and usually entire regions or even the global economy. Moreover, it is natural to think that energy intensity is cross-country correlated, as it depends mostly on technological advances that allow for more efficient methods and to the general development of the world, which includes the spread of ideas, such as environmental protection and the dangers of global warming. The results of reference [38]'s test for cross-country dependence for the three main variables are presented in Table 2, and they clearly show that the three variables are highly cross-country correlated. The other variables that enter into the analysis—schooling and external energy dependence—do not have sufficient observations to perform this test. Despite the fact that there are reasons to believe that these variables are also cross-country dependent, we do not need all the variables to be cross-country dependent to ensure the validity of the application of the common correlated heterogeneous panel data estimator.

Table 2. Cross-Section Dependence.

Variable	Cross-Dependence (CD) Test	*p*-Value	Countries
Energy intensity	307.89	0.000	114
GDP *per capita*	547.61	0.000	156
Industry share	75.85	0.000	81

Notes: The average number of time-series observations is 42.00 for the first test and 45.17 for the second and 38.16 for the third.

As reference [37] observed, "the standard empirical estimators (e.g., fixed effects, difference and system Generalized Method of Moments (GMM)) not only impose homogeneous production technology, but they also implicitly assume stationarity, cross-sectionally independent variables".

The fact that some of our variables (namely, the dependent variable, energy intensity) are non-stationary implies that the usual stationarity error term assumption would be violated.

In the presence of cross-country dependence, individual countries cannot be viewed as independent cross-sections, and consequently, cross-section dependence can affect both inference and identification (see [37,39]). This literature argues that cross-country dependence implies that standard panel data estimators are inefficient, and estimated standard errors are biased and inconsistent. Generally, inconsistency arises as an omitted variable bias when the observed explanatory variables are correlated with the unobserved common factors (see, e.g., reference [40]), such as the shocks mentioned above. Due to both potential non-stationarity and cross-country correlations, traditional methods may not be useful for evaluating the effect of income *per capita*, industry share, external energy dependence, or primary schooling on energy intensity. As a result, we used the [40] common correlated effects mean group estimator—augmented to be robust to reverse causality—to access this empirical relationship. Along the same line, reference [37] argues that this class of heterogeneous estimators is superior to traditional fixed-effects and instrumental variable panel estimators in macroeconomic applications. A similar econometric approach to explain the relationship between country-risk and energy supply was followed in reference [41].

3.3. Specification and Methods

Granger causality is an important issue when evaluating any economic relationship, because it means that an economic series is useful for predicting the behaviour of another series. In this case, it is useful for the determination of whether schooling is important to the prediction of energy intensity (in the Granger sense). This also applies to the relationship between energy use, income, energy dependency, structural transformation and schooling. To that end, we estimated our model using an error-correction model (ECM) approach. This method distinguishes between long run effects and short run effects of the explanatory variables on the energy intensity. According to the econometrics literature cited above, this estimator is robust to (i) country-fixed effects, such as geography and culture or initial technology or natural resources endowment levels; and (ii) unobservable common variables, such as common productivity change or global energy market conditions, which are important factors in this empirical application. In fact, the large time-series that we incorporated into our empirical application allowed us to implement the ECM which offered the following advantages when compared to other approaches: (i) it distinguishes between the short and long run effects of explanatory variables on energy intensity; (ii) the error-correction term can be investigated to determine the speed of energy use adjustment; and (iii) cointegration can be tested in the ECM by closer investigation of the statistical significance of the error-correction term.

The equation for a baseline model to explain energy intensity could be written as follows:

$$E_{it} = \delta_{1i}E_{it-1} + \delta_{2i}y_{it} + \delta_{3i}ind_{it} + \delta_{4i}nei_{it} + \delta_{5i}school_{it} + u_{it}; u_{it} = \alpha_i + \lambda_i'\mathbf{f}_t + \varepsilon_{it} \, , \tag{6}$$

where E_{it} is the energy intensity; *school* is the enrolment in primary school, our variable of interest; y_{it} is the GDP *per capita*; ind_{it} is the industry share in the economy; and nei_{it} is the net energy imported (or energy dependence); $\delta_{1i} - \delta_{5i}$ are the coefficients that measure the (heterogeneous) influence of each of the explanatory variable in energy intensity. The error-correction model version of Equation (6) can be written as follows:

$$\Delta E_{it} = \alpha_i + \rho_i(\beta_{1i}E_{it-1} - \beta_{2i}y_{it-1} - \beta_{3i}ind_{it-1} - \beta_{4i}nei_{it-1} - \beta_{5i}school_{it-1} - \lambda_i'\mathbf{f}_{t-1}) \tag{7}$$

$$+\gamma_{1i}\Delta y_{it} + \gamma_{2i}\Delta ind_{it} + \gamma_{3i}\Delta nei_{it} + \gamma_{4i}\Delta school_{it} + \gamma_i\mathbf{\Delta f}_t + v_{it}, \tag{8}$$

where β_{ji} stands for the long run equilibrium relationship between energy intensity, income, schooling and the other covariates, and γ_{ji} stands for the short run relationship between those variables. With $\beta_{5i} = \gamma_{4i} = 0$, we would have the ECM version without schooling, a version whose results we will also present to compare with our baseline one. The factor $\mathbf{f}_t$ represents the common factors that influence the evolution of energy intensity, GDP, industrial share (or structural transformation) and schooling in different countries, such as technological, political, educational and energy supply shocks. Although these factors are common to all countries, their influences in each country can be different as λ_i and γ_i are country-specific coefficients. Along these lines, the model incorporates the full heterogeneous effects of GDP, structural transformation and schooling on the energy intensity across countries. The estimated equation can thus be re-written as

$$\begin{aligned}\Delta E_{it} = \pi_{0i} + \pi_{1i}E_{it-1} + \pi_{2i}y_{it-1} + \pi_{3i}ind_{it-1} + \pi_{4i}nei_{it-1} + \pi_{5i}school_{it-1} + \pi'_{Fi}\mathbf{f}_{t-1} + \\ + \pi_{6i}\Delta y_{it} + \pi_{7i}\Delta ind_{it} + \pi_{8i}\Delta nei_{it} + \pi_{9i}\Delta school_{it} + \pi'_{fi}\mathbf{\Delta f}_t + v_{it},\end{aligned} \quad (9)$$

where $\pi_{1i} = \rho_i$.

From the regression results, the long run coefficients, β_{ji}, in (8) can be obtained dividing the estimated coefficients from Equation (9), π_{ji} by ρ_i (β_{ji}=$-\frac{\pi_{ji}}{\rho_i}$), which is the speed of convergence of the energy intensity to its long run equilibrium. Inference on the coefficient for the lagged energy intensity will indicate the presence of a long run equilibrium relationship. If $\rho_i = 0$, there will be no error correction and the model will reduce to a regression with variables in the first-differences (the level term in brackets in Equation (8) disappears). However, if $\rho_i \neq 0$, we observe error-correction, meaning that following a shock, the economy returns to its energy intensity long run equilibrium path and thus, cointegration exists between the variables and processes in brackets (in Equation (8)). As noted above, we also estimated a restricted model with $\pi_{5i} = \pi_{9i} = 0$, i.e., without school in the regression.

In accordance with the econometric literature ([40,42]), we added cross-section averages of all variables in the model (energy intensity, GDP *per capita*, industry share and primary school enrolment) to Equation (9). This procedure replaces the unobservable and omitted elements of the cointegration relationship. However, reference [43] showed that this approach may suffer from a small sample bias, especially in panels with time-series of moderate dimensions. Thus, they offered a strategy to deal with weakly exogenous regressors which is robust to reverse feedback. As argued by the mentioned authors, the inclusion of lags will strengthen the estimations to reverse causality, meaning that the estimated coefficients may be regarded as measuring the effect of schooling (and of the other explanatory variables) on energy intensity and not the other way around. In fact, the study of a potential effect of energy intensity on schooling is beyond the scope of this article. However, the effect of energy consumption (related to energy intensity) has been study by others (e.g., reference [44]) and is also beyond the scope of this study. We followed their suggestion including further lags of the cross-section averages mentioned above.

$$\sum_{l=1}^{p}\tau_{1il}\overline{\Delta y}_{t-p} + \sum_{l=1}^{p}\tau_{2il}\overline{\Delta ind}_{t-p} + \sum_{l=1}^{p}\tau_{3il}\overline{\Delta nei}_{t-p} + \sum_{l=1}^{p}\tau_{4il}\overline{\Delta school}_{t-p} + \sum_{l=1}^{p}\tau_{5il}\overline{\Delta E}_{t-p}. \quad (10)$$

In particular, we followed the rule of thumb in that reference ([43]) to choose the number of lags to be included ($p = T^{1/3}$). In a time-series of near 40 years on average, that rule of thumb indicated a value between 3 and 4. In ECM, this corresponds to adding two or three lagged differences. We chose to include three lagged differences.

4. Results

We estimated Equation (9) and show the results in Table A1. Columns (1) and (2) show the model specification without schooling and column (3) shows the model specification with primary schooling as an explanatory variable.

4.1. Estimation Quality Tests and Evidence

We estimated regressions from a large panel database with more than 1200 observations and an average of more than 30 time-series observations for nearly 40 countries. In general, data included in regressions began in 1950 and ended in 2009, although this varied across countries as is natural for an unbalanced panel. In the Appendix, we include a list of the countries that were used in the analysis with information about their respective time spans. Note that due to the availability of data, the database is mostly composed of developed and developing countries, including very few poor countries. This is the largest database ever reported in the literature—in both time-series and cross-section dimensions—to approach the determinants of energy intensity. There was evidence of error-correction. The lagged energy intensity variable was highly statistically significant and negative with an implied half-life—an indicator of the speed of adjustment of energy intensity following a shock, computed as $ln(0.5)/ln(1+\pi_{1i})$—of 1 year and 7 months. In any event, these are very fast speeds of adjustment for the energy intensity. Thus, this study confirms the high convergence of energy intensity found in the literature using other methods (e.g., in reference [2]). In the table, we present diagnostic tests related to stationarity and cross-section dependence, the issues for which the used method is particularly robust. The *Stat-test* (*res*) rejected the unit-root null hypothesis for the error term which indicates that the econometric approach corrected for the non-stationarity found in data, as expected. Concerning the cross-correlation of the error term, we present the *CD-test* (*res*). From the analysis of the results, we can say that all the residuals presented less evidence of cross-sectional correlation than the dependent variable did (compare with the results in Table 2), in line with what has been argued by, e.g., reference [45]. Notably, in the regression of column (3) with schooling included, the test did not reject the null of no cross-sectional dependence, suggesting that in this case, the method completelly corrected for cross-sectional dependence. Finally, the Wald test indicated the overall significance of the regressions.

An important (and not so common) feature of these estimations is that there was a high number of observations per country but not much oscillation between them (the minimum number of observations per country was 26 or 31 depending on the regression, and the average was 32 or 33, respectively. This feature of the data is important as it deals with the point raised by reference [46] which argued that the estimator in reference [40] is adequate for panel databases with a large-T dimension, in order to avoid the small sample bias. Also, reference [43] showed that the cross-sectionally averaged augmented common correlated effects (CCE) estimator (used in the estimations in Table A1) performs quite well in the presence of heterogeneous coefficients, weakly exogenous regressors and persistent factors, but can be affected by the time-series bias if T is small. Additionally, references [43,46] argued that the bias affecting regressors (in our case, GDP *per capita*, schooling and industry share) other than the lagged dependent variable (in our case the *lagged* energy intensity) is just a proportion of the bias affecting the lagged dependent variable. Applying these arguments to our empirical application and given a quite large T-dimension in our database, we argue that the coefficients on income, schooling, industrial share and energy dependence should not be affected (much) by the time-series bias.

4.2. Interpretation of the Regression Results

When primary schooling was considered (column 3), there were long run negative effects of primary schooling (on energy intensity), industrial share (positive on energy intensity), and external energy dependence (negative on energy intensity). We tested the same regressions by substituting primary schooling by secondary and tertiary schooling (from the same source of data) and these two last variables were revealed to be not statistically significant—see the results in the Appendix. In the light of the discussion of the effect of schooling in environmental awareness which we made in the Introduction, there is not a consensus on the micro and case studies for which of the level of education is more important. Thus, our contribution highlights primary schooling to be the most important. We thank a referee for calling our attention to this issue. A short run positive effect of energy external dependence also appeared in this regression. Quantitatively, a one percentage point increase in primary school enrollment reduced the energy intensity by 0.05% of the GDP *per capita*. A one percentage point increase in primary school enrolments is completely feasible in the process of development of a country. Looking at Table 1, the standard deviation for primary school enrolments is nearly 5 percentage points, meaning that just a one standard deviation increase in primary schooling enrolment would decrease the energy intensity by 0.25% of the GDP *per capita*. For example, India grew by nearly 8 percentage points in primary school enrolments just between 2000 and 2008. When looking at the values of Table 1, one could observe that the energy intensity ranges from 0.6% of GDP (minimum) and has an average of 80% of GDP. This means that an average country, that in one year grew roughly 1 standard deviation in primary school enrolment per capita, decreased from 80% of GDP (taking the mean as the initial point) to 79.75%. In 8 years, this should amount to nearly 78%. In 30 years, this means that a country could decrease its energy dependency to 72.5%, representing almost 10% of the initial value. If a country departs from an initial value of 20% of energy intensity, a decrease of 8.5% represents almost halving the initial value, which can only be regarded as a quantitative meaningful effect—and this could be obtained just with the effect of schooling. In the following paragraph, we analyse the quantitative effects of other variables.

An increase of one percentage point in the share of industry contributed to an increase in energy intensity of 1.8% of the GDP *per capita* which is a very important effect when we recall that energy intensity ranges from 0.6% of GDP (minimum) and has an average of 80% of GDP. Finally, a 1 USD increase in energy dependency decreased the energy intensity by 0.001% of GDP *per capita* in the long run and increased it by 0.001% in the short run. Again, looking at Table 1, the standard deviation of energy dependency was 63021 USD; thus, a standard deviation increase in external dependency would decrease energy intensity by 63.02% of GDP *per capita* in the long run and increase it by 63.02% in the short run, which is undoubtfully a high quantitative effect.

Interestingly, in this regression, the income variable was not statistically significant in explaining the decline in energy intensity, in the short, nor the long run, which was a common result in previous empirical work on energy intensity. This may indicate that schooling tends to substitute income in explaining the decline in energy intensity.

Because of that and to better assess the effect of schooling in explaining energy intensity, we wanted to compare the results with the models in which we excluded schooling from the set of regressors (columns (1) and (2)). While in the case presented in column (1), we used all the available data after excluding schooling, in column (2), we fixed the same database that was used in the baseline regression in column (3) so that, in this case, differences in results were not dependent on differences in the database.

In the regression presented in column (1), a 1 unit increase in income *per capita* variations decreased the energy intensity by 0.07% of GDP *per capita* in the short run. However, an increase in the net energy dependence variation of 1 USD would increase energy intensity by 0.003% of GDP *per capita* in the short run. Thus, in this regression, only statistically significant results were shown in the short run. In column (2), also without schooling, but with the same sample as in the regression with schooling, all results were maintained (here, a 1 unit increase in income *per capita* variations decreased energy intensity by 0.05% of GDP *per capita* in the short run), but there was an additional statistically significant result—external energy dependence also decreased the energy intensity in the long run by 0.002% of GDP *per capita*.

When comparing one regression to another, it seems that primary schooling and deindustrialization are the most important explanations for the decline in energy intensity in the long run after the second half of the 20th century, while the external energy imbalance seems to have been the most influential variable both in the long and in the short run, working to decrease energy intensity in the long run but increasing it in the short-run.

The effect of schooling *as a substitution* for income as a (negative) determinant of energy efficiency was not determined by the different samples in the regressions. In fact, column (2) shows a relationship that does not include schooling but maintains the smaller sample. This confirms that the negative effect of income on energy intensity vanishes when schooling is introduced, even when exactly the same sample is maintained.

5. Shortcomings, Limitations and Prospects for Future Research

This study presents the limitations relative to the single econometric method and the dataset that were used. However, we think that the method used was quite appropriate to the nature of data (see, again, reference [37]), as it is robust to non-stationarity, cross-dependency and heterogeneous effects. Additionally, the method also accounts for the omitted variable bias and reverse causality due to common factors but has heterogeneous effects inside different countries—all important issues that affect macroeconomic data in general and in our dataset in particular. In fact, causality was approached with the error-correction method and by the introduction of lags of the explanatory variables, which is the general approach for dealing with causality in econometrics (e.g., in other dynamic or system GMM panel estimators, as initiated by reference [47]). However, it should be noted that the method accounts for causality *à la Granger* (schooling helps to predict energy intensity) which does not exactly mean that schooling *cause* energy intensity (decreasing it). This is a problem caused by the use of secondary data and econometric methods. Future research may overcome this issue in the field of experimental economics or through the study of cases monitoring the *effective* causality between schooling (or education for environmental awareness) and the future behaviour of children or young adults. Studies using twins could handle this issue. In fact, as argued by reference [48], the study of twin pairs is consistent with a causal effect of lifestyle factors on important late-life outcomes, which may be the object of future work.

As argued in reference [45], non-linearities are difficult to deal with this method and in order to apply the correct methodology to address non-linearities we would need a larger database than the one used in this paper. Note that a larger database would come in the expense of dropping covariates that were already tested in econometric explanations of energy intensity which would lead to obvious omitted variable bias.

The used data came from a credible database that is widely used in macroeconomics. Additionally, after various attempts to improve coverage by concatenating different data sources, this was the one that provided the widest possible panel for the variables used. However, it had also some drawbacks. In particular, it is important to note that a reasonable proportion of the countries data ends in 1980 (see Appendix for a complete description of the countries and years covered). In fact, data ends in 1980 for 17 out of 52 (33%) countries in column (1) (Table 3) and 12 out of 39 in columns (2) and (3) (31%). To overcome this issue, country studies which using quarterly data on energy intensity and schooling may be an avenue to be pursued by future research.

Table 3. Schooling, income and energy intensity.

	(1) Without School-Enlarged Sample	(2) Without School-Same Sample	(3) With School
Income per capita$_{t-1}$	−0.0001 (0.313)	−0.0001 (0.188)	−0.0001 (0.384)
Δ Income per capita$_t$	−0.0007 *** (0.000)	−0.0005 *** (0.000)	−0.004 (0.192)
Industry Share$_{t-1}$	−0.009 (0.140)	−0.005 (0.458)	0.018 ** (0.027)
Δ Industry Share$_t$	0.004 (0.425)	0.03 (0.574)	0.015 (0.236)
External Dependence$_{t-1}$	−0.0000 (0.174)	−0.00002 ** (0.023)	−0.0001 * (0.100)
Δ External Dependence$_t$	0.00003 *** (0.003)	0.00003 ** (0.010)	0.091 ** (0.034)
Primary School$_{t-1}$	—	—	−0.0005 *** (0.002)
Δ Primary School$_t$	—	—	−0.0001 (0.615)
Error Correction Coefficient E_{it-1}	−0.353 *** (0.000)	−0.355 *** (0.000)	−0.350 *** (0.000)
N Observ.	1631	1266	1266
Avr. N Obs.	31.4	32.5	32.5
Min–Max	26–35	31–35	31–35
Number Countries	52	39	39
Wald	152.22 ***	136.85 ***	65.31 ***
CD-test (res)	2.98 *** (0.003)	2.52 ** (0.012)	-0.36 (0.718)
Stat-test (res)	rejects I(1)	rejects I(1)	rejects I(1)

Note: The dependent variable is energy intensity (energy consumption/GDP). Values in parentheses below the coefficients are p-values from robust (clustered) standard errors. The regressions include two lags of lagged differences of cross-section averages. Level of significance: *** for p-value < 0.01; ** for p-value < 0.05; * for p-value < 0.1. The Wald test is a joint significance test for the regressors. The CD-test is a Pesaran (2004) cross-section dependence test on the null value of cross-section independence done on the residuals from the regression (p-value presented in parentheses). The stat-test is the [49] unit root test made on the residuals. This test used four lags and rejected I(1), which means that in all lags, the test of the unit root rejects with and without a trend. The list of countries that were used in the regressions is available upon request.

6. Conclusions and Policy Implications

The energy intensity (the ratio of energy use or consumption to GDP—which can also be seen as an indicator of eco-efficiency) is one of the most debated indicators that relate to development and environment protection and thus, to the creation of a circular economy. In this paper we illustrate that schooling can have an effect on decreasing energy intensity, thus improving worldwide eco-efficiency and helping to establish a circular economy. If levels of schooling prove to be effective in decreasing the intensity in the use of energy, then they are contributing to a more ecologically efficient world. The establishment of a circular economy depends crucially on the capacity to minimize the use of non-renewable resources, pollution and waste for which ecological efficiency is a necessary condition.

First, we devised a simple model that explains the effect of schooling based on the trade-off between consumption and schooling and on the influence knowledge should have in decreasing the intensity in the use of energy. In aggregate terms, the growth rate of energy intensity was shown to be dependent (positively) on the difference between the growth rate of consumption and the growth rate of human capital and, as a result of that, energy intensity declined.

In an empirical application, we used an econometric estimator that is indicated for macroeconomic large panel databases—with non-stationary data and cross-section dependence—which has recently became available in the econometrics literature to address the determinants of energy intensity, namely schooling. Our results presented a significantly negative long run effect of primary schooling enrollment on energy intensity. Furthermore, there was a negative influence of income on energy intensity in the short run that vanished, however, when primary schooling enrollment was included in the regression. This effect of primary schooling as a *substitute* for income *per capita* in explaining the diminishing energy intensity that has been verified around the world may be explained by the effect that this level of schooling has on the demand for new cleaner technologies that help to decrease energy intensity. At least two reasons may be attributed to be beyond the importance of primary schooling: (i) the primary schooling enrolment is a proxy for the investment a society is making on basic education, and environmental awareness belongs to the set of basic education concepts; and (ii) basic education of children, including environmental awareness, influences whole families to decrease their energy use or intensity (i.e., children influence their own families' behaviours). However, further research is needed to establish this in case or experimental studies. The satisfaction of basic consumption needs at low income levels may justify why energy intensity decreases only for higher development levels.

All in all, it seems that primary schooling and deindustrialization are the most important explanations for the decline in energy intensity in the long run after the second half of the 20th century, while the external energy imbalance seems to be the most influential variable both in the long and in the short run, working in order to decrease the energy intensity in the long run but decreasing it in the short run.

Our results highlight important policy implications. In the design of public educational policy, policy makers should be aware of this effect of primary schooling on the decrease of energy intensity, such that educational policy (targeted at primary schooling) may be seen as a substitute to public efforts to reduce the consumption of energy and to increase environmental protection. Thus, the use of revenue from taxes on energy consumption may have reinforcing effects if applied in primary schooling. Also, the primary schooling syllabus should include issues related to energy use and consumption, environmental responsible behaviour, environment protection and the danger of global warming, as these should affect future generations' behaviour towards energy use and thus, worldwide eco-efficiency and the establishment of a truly circular economy.

This paper open the prospect of further research on the empirical relationship between education and energy efficiency, substituting the focus that the literature has on the relationship with income. Analysis of this relationship, both in micro and experimental studies, may complement the evidence presented here.

Author Contributions: T.S. designed the research idea, did the literature review, developed and solved the theoretical model, analysed the results and wrote the text. M.S. collected the data and performed the statistical and econometric work, wrote the appendix and adapted the text to the sustainability template.

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Appendix A. Alternative Results: Secondary Schooling

Table A1. Schooling, income, and energy intensity: alternative results to secondary schooling.

	(1) Without School-Enlarged Sample	(2) Without School-Same Sample	(3) With School
Income per Capita$_{t-1}$	−0.0001 (0.313)	−0.0001 (0.134)	−0.0002 (0.461)
Δ Income per Capita$_t$	−0.0007 *** (0.000)	−0.0007 *** (0.000)	−0.0003 (0.794)
Industry Share$_{t-1}$	−0.009 (0.140)	−0.004 (0.488)	0.0002 (0.119)
Δ Industry Share$_t$	0.004 (0.425)	0.02 (0.663)	−0.0004 (0.103)
External Dependence$_{t-1}$	−0.0000 (0.174)	−0.00001 ** (0.023)	−0.00001 * (0.058)
Δ External Dependence$_t$	0.00003 *** (0.003)	0.00003 *** (0.007)	0.00006 *** (0.000)
Secondary School$_{t-1}$	—	—	−0.0003 (0.461)
Δ Secondary School$_t$	—	—	−0.0003 (0.794)
Error Correction Coefficient E_{it-1}	−0.353 *** (0.000)	−0.367 *** (0.000)	−0.363 *** (0.002)
N Observ.	1631	1266	1266
Avr. N Obs.	31.4	32.5	32.5
Min–Max	26–35	31–35	31–35
Number Countries	52	39	39
Wald	152.22 ***	67.41 ***	67.41 ***
CD-test (res)	2.98 *** (0.003)	2.54 ** (0.011)	0.71 (0.480)
Stat-test (res)	rejects I(1)	rejects I(1)	rejects I(1)

Note: The dependent variable is energy intensity (energy consumption/GDP). Values in parentheses below coefficients are *p*-values from robust (clustered) standard errors. The regressions include two lags of lagged differences of cross-section averages. Level of significance: *** for *p*-value < 0.01; ** for *p*-value < 0.05; * for *p*-value < 0.1. The Wald test is a joint significance test for the regressors. CD-test is a Pesaran (2004) cross-section dependence test on the null value of cross-section independence done on the residuals from the regression (*p*-value presented in parentheses). The Stat-test is the Pesaran (2007) unit root test made on the residuals. This test used four lags and rejected I(1) meaning that in all lags, the test of the unit root rejects with and without a trend. The list of countries were used in regressions is available upon request.

Appendix B. Sample Coverage: Countries and Years

Appendix B.1. Column 1

Argentina (1950–1980); Australia (1950–1980); Belgium (1950–1980); Bolivia (1950–2006); Brazil (1950–2008); Bulgaria (1950–2009); Burma (1952–1980); Canada (1950–2009); Chile (1950–2009); China PR(1959–2008); Colombia (1950–2008); Costa Rica (1953–2008); Czechoslovakia (1950–1980); Denmark (1950–2008); Ecuador (1950–2008); El Salvador (1955–2008); Finland (1957–2008); France (1950–2008); German DR (1953–1980); German FR (1953–1980); Greece (1950–2008); Guatemala (1950–2008); Hungary (1950–2008); India (1951–1980); Indonesia (1953–2008); Iran (1950–2007); Ireland (1950–1980); Italy (1950–2008); Japan (1956–2008); Korea, South (1952–2008); Liberia (1950–1980); Mexico (1950–2008); Netherlands (1950–1980); Nicaragua (1950–2008); Norway (1950–2008); Pakistan (1951–2008); Peru (1950–1980); Philippines (1950–2008); Poland (1957–2008); Portugal (1950–2008); South Africa (1950–2008); Spain (1950–2008);

Sweden (1950–1980); Switzerland (1950–1980); Thailand (1957–2008); Turkey (1950–1980); USSR (Russia) (1950–1980); United Kingdom (1950–2008); United States (1950–2008); Uruguay (1950–2008); Venezuela (1950–2008); Yugoslavia (1955–1980).

Appendix B.2. Column 2

Argentina (1950–1980); Australia (1950–1980); Belgium (1950–1980); Bolivia (1950–2006); Brazil (1950–2008); Bulgaria (1950–2009); Burma (1952–1980); Canada (1950–2009); Chile (1950–2009); China PR(1959–2008); Colombia (1950–2008); Costa Rica (1953–2008); Czechoslovakia (1950–1980); Denmark (1950–2008); Ecuador (1950–2008); El Salvador (1955–2008); Finland (1957–2008); France (1950–2008); German DR (1953–1980); German FR (1953–1980); Greece (1950–2008); Guatemala (1950–2008); Hungary (1950–2008); India (1951–1980); Indonesia (1953–2008); Iran (1950–2007); Ireland (1950–1980); Italy (1950–2008); Japan (1956–2008); Korea, South (1952–2008); Liberia (1950–1980); Mexico (1950–2008); Netherlands (1950–1980); Nicaragua (1950–2008); Norway (1950–2008); Pakistan (1951–2008); Peru (1950–1980); Philippines (1950–2008); Poland (1957–2008); Portugal (1950–2008); South Africa (1950–2008); Spain (1950–2008); Sweden (1950–1980); Switzerland (1950–1980); Thailand (1957–2008); Turkey (1950–1980); USSR (Russia) (1950–1980); United Kingdom (1950–2008); United States (1950–2008); Uruguay (1950–2008); Venezuela (1950–2008); Yugoslavia (1955–1980).

Appendix B.3. Column 3

Argentina (1950–1980); Australia (1950–1980); Belgium (1950–1980); Bolivia (1950–2006); Brazil (1950–2008); Bulgaria (1950–2009); Canada (1950–2008); Chile (1950–2009); Colombia (1950–2008); Costa Rica (1953–2008); Czechoslovakia (1950–1980); Ecuador (1950–2007); France (1950–2008); Greece (1950–2007); Guatemala (1950–2008); Hungary (1950–2008); Iran (1950–2007); Ireland (1950–1980); Italy (1950–2008); Korea, South (1952–2008); Liberia (1950–1980); Mexico (1950–2008); Netherlands (1950–1980); Nicaragua (1950–2008); Norway (1950–2008); Pakistan (1951–2008); Peru (1950–1980); Philippines (1950–2008); Portugal (1950–2008); South Africa (1950–2008); Spain (1950–2008); Sweden (1950–1980); Switzerland (1950–1980); Turkey (1950–1980); USSR (Russia) (1950–1980); United Kingdom (1950–2008); United States (1950–2008); Uruguay (1950–2008); Venezuela (1950–2008).

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sustainability

Article

An Integrated Sustainable Supplier Selection Approach Based on Hybrid Information Aggregation

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Abstract: With a great emphasis on both social and environmental responsibilities, sustainable supply chain management has gradually been adopted and promoted as an innovative business model. In sustainable supply chain practice, the choice of sustainable suppliers relates to the long-term development of a company. While the environmental performance of suppliers has been commonly considered, the social dimension has not yet received enough attention. This paper first proposes a novel criteria system for evaluating sustainable suppliers from three aspects and six dimensions, and then introduces an integrated evaluation model with a novel hybrid information aggregation. To verify the applicability and effectiveness of the proposed method, a real case of a large supermarket is introduced and analyzed. The research results show that (1) the indicator system based on Triple Bottom Line theory can serve as a framework of sustainable supplier selection for manufacturing and circulation enterprises; (2) the introduction of hybrid information aggregation can effectively handle the uncertainties of indicator scores under the realistic fuzzy environment and objectively reflect the intentions of the scorers; and (3) in comparison with the TOPSIS algorithm, the priority order finally obtained is consistent, but the proposed model shows more robustness in the sensitivity test.

Keywords: sustainable supplier selection; DEMATEL; ANP; fuzzy VIKOR; IVTFN; hybrid information aggregation; TBL theory

1. Introduction

The problems regarding violations of corporate ethics and national laws caused by the lack of environmental and social responsibility in supply chain operations have drawn great public concern in recent times [1,2]. On 31 August 2011, five environmental groups led by the Institute of Public and Environmental Affairs (IPE), a nonprofit organization in Beijing, revealed a pollution map with regard to the supply chain of the high-tech giant Apple in China after more than six months' investigation, which exposed dozens of labor rights violations, as well as safety and environmental offenses, made by 27 suspected suppliers of Apple. Subsequently, The Other Side of Apple II, a special report issued by IPE in association with other green groups strongly condemned Apple for the environmental and social irresponsibility of its business practices. Incidents included the long-term breach of environmental regulations by the factories of some suppliers, with more than ten violations of commitments to pollution and worker health accords, violations of international safety standards for the release of toxic metals such as copper and nickel, a lack of attention to the physical and mental health of the local community and public, and the disposal of hazardous wastes in a manner that violated local governmental legislation [3]. Initially, Apple denied all the charges and argued that they were just downstream purchasers that had no joint liability for bad behavior among other suppliers. However, Chinese environmental organizations and consumers did not agree with this statement, and started to boycott all Apple products. In the face of growing public pressure, Apple came to realize that they were unable to ignore the problem, since consumers place liability on the focal company in the product chain more often than not. For focal companies, they should not only manage their own behavior, but also strengthen the supervision of the operations of their suppliers. Consumers in modern society are increasingly concerned about whether the products they buy are environmentally sound, and whether the brands they trust maintain a responsible supply chain. In view of the public scrutiny and social pressure, core companies cannot only concern themselves with their own transparency and green obligations; the issue of whether upstream suppliers take sustainable initiatives is directly linked to the reputations of focal firms and the supply chain at large. Therefore, they should pay much more attention to sustainable supply chain management (SSCM), especially in terms of the choice of sustainable suppliers. For purchasing managers and researchers, how to establish a practical and pragmatic evaluation system and method focusing on sustainable suppliers has become a necessary but challenging issue [4–7].

The sustainable supplier selection (SSS) is a focus issue that has gained attention over the past five years [8,9]. Compared to traditional supplier selection which mainly concentrates on economic benefit and cost optimization [10–12], and green supplier evaluation that focuses on environmental performance [2,13,14], investigation of the sustainability of suppliers also needs to consider their social responsibility. The indicators of responsibility to internal stakeholders around employee rights have been put forward: occupational health and safety [4,15–17], training and practice [15,18], and other legitimate rights [4,15]. However, few works paid attention to external stakeholders, much less did they establish a comprehensive evaluation framework and logic that could be used to measure the sustainability of the supplier. Therefore, the first potential contribution of this paper is to place a stronger emphasis on suppliers' social performance, and to propose a novel measure for SSS based on the logic of the Triple Bottom Line (TBL) theory [19]. This measure covers economic, green (environmental), and social factors, with a total of 24 indicators. Among them, from stakeholder theory we point out that suppliers' social responsibility is not only reflected in their duties to internal stakeholders (such as employees and shareholders), but also to external stakeholders (such as communities and the governments).

Considering the criteria of SSS, a multi-criteria decision-making (MCDM) approach provides an effective framework to solve the screen problem with different conflicting goals [6]. Some typical MCDM methods, such as the Analytic Network Process (ANP), have been widely used to solve supplier selection issues, while most studies have assumed that each cluster in the ANP has equal weight in the creation of a weighted supermatrix [20,21]. In addition, many used methods, including Artificial Neural Networks (ANNs), rarely consider the real existence of mutual influence and feedback among criteria during the process of weight determination [22]. To improve upon these shortcomings, we integrate the DEMATEL method, representing the related properties between indicators with the ANP method to calculate the weights of the various criteria. Compared with other studies proposing the DEMATEL-ANP method [21,23], we improve the method for remapping the ANP network structure, which effectively reduces computation costs.

TOPSIS and VIKOR are typical compromise programming technologies which focus on ranking and selecting a set of options [24]. Compared with the TOPSIS method, which may cause an improper effect known as "total rank reversal" [2], the fact that the best solution obtained by VIKOR is closer to the ideal solution makes VIKOR the most suitable method for selecting suppliers in the view of many authors [25]. In light of the above factors, this paper also uses a hybrid VIKOR technology as a decision-making tool to determine the optimal sustainable supplier before the weight definition through DEMATEL-ANP method is applied.

Moreover, this paper also introduces a set of hybrid information aggregation for practical evaluation, and combines this information set with the proposed integrated method. As qualitative factors and quantitative indicators often coexist simultaneously in the measure of supplier selection, accuracy and pragmatism cannot be achieved if those factors are scored by a single value type [26]. For the convenience of calculation or the limitation of the method, using mixed data as an input was generally not considered in the past; rather, it served to unilaterally adopt quantitative scoring or qualitative judgment. The hybrid information aggregation we proposed can reduce the vague and subjective impact of human judgments and preferences through mixed data forms to describe the comprehensive performance of potential suppliers, which includes the precise number, interval number, and fuzzy number. Note that the linguistic term, rather than the numerical form, is proposed for decision makers (DMs) to answer the relevant questions [4], due to its simplicity and tangibility in expressing perceptions [4], which can normally be transformed into fuzzy numbers. The use of an interval-valued triangular fuzzy number (IVTFN) is proposed in this paper to effectively reduce the uncertainty and ambiguity that exists in the supplier selection process [27].

A case of a retail enterprise is finally introduced to verify the applicability of the measure and feasibility of the proposed model with regard to the SSS problem. While most related literature in this field has focused on manufacturing companies [28–30], little attention is given to SSS of retail enterprises. As more and more retail companies, such as Wal-Mart and Migros, have proposed goals and plans for global sustainable procurement in recent years, the means of developing a comprehensive measure for sustainability and an effective assessment method to choose sustainable suppliers has become an urgent problem. We contribute theoretical supplements for the field of supplier selection and the question of sustainability by pointing out the limitations of the existing methods and proposing an effective model and information process approach to guide enterprises through the supply chain, especially in the retail industry, to select sustainable suppliers and implement sustainable practices.

The remainder of this paper is organized as follows: Section 2 reviews the literature on SSCM, SSS criteria, and evaluation methods. Section 3 introduces our methodology, including the DEMATEL-ANP-VIKOR algorithm and hybrid information aggregation. In Section 4, an empirical case of a retail enterprise is presented to solve the SSS problem by an integrated approach. Finally, in Section 5, we discuss the implications and offer conclusions and future study avenues.

2. Literature Review

2.1. SSCM and Supplier Selection

The earliest study of SSCM can be traced back to the 1990s, when the concept of sustainability mainly referred to environmental management. Drumwright [31] put forward the importance of social responsibility for companies in terms of purchasing, production, and consumption. In the same year, Murphy, et al. [32] suggested that priority should be placed on environmental issues over logistics management. In the late 1990s, the principles of green supply chains were proposed to change the traditional requirements and objective functions goals of operation management [33,34]. Elkington [19] further proposed the concept of TBL, focusing on the balance of economic, environmental, and social goals from a business perspective. Carter and Jennings [35] posed the dual relationship approach to analyze each system unit so as to assess change in the case where a sustainable solution was used. Mentzer, et al. [36] believed that sustainability in the supply chain is a systematic and strategic coordination of business operations and decisions within a company and its supply chain to increase the long-term comprehensive benefits. Linton, et al. [37] was the first to put forward the concept of SSCM, while Carter and Rogers [38] and Seuring and Müller [1] offered deeper explanations of this term. Specifically, SSCM was described as a strategic and transparent collection that covered four support aspects of sustainability, namely: risk management, transparency, strategy, and corporate culture [38], coordinating the systematic business process based on the TBL principle within internal organizations [1], to eventually get the trade-off from social, environmental, and economic objectives. Companies should have a formal mechanism to monitor and disclose responsible and sustainable issues in their supply chain [39] in order to gain both internal and external performance edges and reputations, as well as continuous competitive advantages [1,40,41].

As a critical part of SSCM, helping suppliers recognize the importance of sustainability and support them in improving their SSCM practices is a vital task for core enterprises [5]. Only by the efforts of sustainable initiatives taken through the integration of upstream and downstream partners, can sustainability in the supply chain be continued. The core enterprise can actively mobilize their suppliers to participate in environmental protection plans, doing charities, and maintaining cooperative partnerships, and encourage them to address SSCM initiatives and adopt more proactive environmental strategies [42]. In fact, suppliers who positively participate in the practice of SSCM can reduce the potential risks from environmental and political uncertainty, as well as economic volatility, through the full supply chain, and can ultimately earn the praise of downstream customers for outstanding performance in terms of sustainability [43].

Previous literature concerning supplier selection mostly focused on economic and environmental factors [44–49], while recent studies have begun to increase the consideration of suppliers' social performance when selecting sustainable suppliers [6,7,50]. Apparently, sustainable suppliers have dramatic differences in operation goals, contract models, relationships, and evaluation standards compared with traditional suppliers and green suppliers, as demonstrated in Table 1. To maximize the value of the entire supply chain, focal firms need to carefully select raw material suppliers and product distributors. As the front end, in sustainable supply chains (see in Figure 1), those raw material suppliers are the base of value development, transmission, and even enhancement. That means that sustainable suppliers play a crucial part in the implementation of SSCM initiatives, which can deliver the benefits of both environmental improvements and cost reductions within the supply chain to the downstream through material flows [29].

Table 1. The distinction between traditional suppliers, green suppliers, and sustainable suppliers.

	Organizational Objectives	Relationship in Supply Chain	The Number of Suppliers	Evaluation Standards
Traditional suppliers	Maximum benefit of economy	Short-term and rival strategy	Scattered suppliers	Price, quality and delivery
Green suppliers	Maximum benefits of economy and environment	Green cooperation and competition	Suppliers integration	Economy and environment
Sustainable suppliers	Maximum benefits of economy, society and environment	Partner for creating new value through SSCM	Suppliers integration	Considering the TBL factors

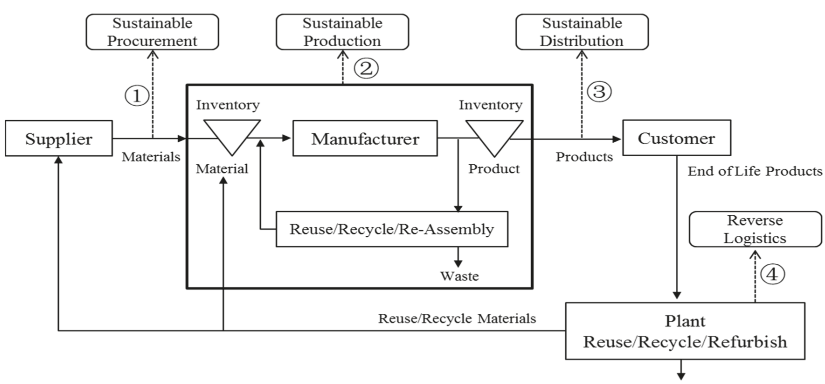

Figure 1. The main activities in a typical SSCM [8].

2.2. *Sustainable Supplier Selection Criteria*

The evaluation system of supplier selection can be traced to the work of Dickson [51], who earlier presented a measure coving 23 economic indicators. Weber, et al. [52] reordered the priority of indicators most proposed by Dickson [51] based on citation frequency over the past two decades, and further revealed the evolution trend of these classical criteria. They found that some criteria, like price, quality, delivery time, production equipment, and capacity, still occupied the primary positions, whereas other indicators changed significantly as a result of shifts of focus by academia and industry. For example, the relative importance of financial conditions was on the rise, while the ranking of location dropped, since the geographical position was no longer a restraining factor for suppliers due to the rapid development of the logistics industry. After the 1990s, the measure of supplier selection received more attention when some scholars refined partial factors including purchased price, product quality, and delivery time, and further proposed second-grade and even third-grade indicators in order to make assessments quantifiable and comparable [10,46,48]. The cost (or purchase unit price), for instance, was subdivided into fixed costs, design costs, supply costs, technical expenses, after-sales service costs, and inventory costs, and so forth. Later on, with the view of Business Process Reengineering (BPR) causing great repercussions [53], capabilities including resource integration, supply flexibility, and information technology have received unprecedented attention [54], and were also added to the supplier evaluation system for core enterprises to measure their suppliers' performance. In the face of the competitive environment that came with economic globalization, the ability and responsibility of suppliers are expected to remain at a much higher level, in terms of factors such as compliance with local regulations, assuming client responsibilities proactively, identifying supply chain risks, and so forth. As global attention has turned to sustainable development [55] and Green supply chain management (GSCM) [56], environmental performance has gradually become a crucial factor in the selection of potential suppliers (especially green suppliers), while social performance was hardly mentioned until corporate social responsibility (CSR) [31] and the TBL theory [19] drew much attention to it. Some scholars have focused on this issue but have not yet established a generally accepted measure for supplier social responsibility [7,9,17,18,57].

Based on the three dimensions in the TBL framework [19], indicators affecting supplier selection in the last 20 years or so were classified into the economic, environmental, and societal metrics. The research on traditional supplier evaluation generally only concerned economic performance [45,58–61]. Table 2 summarizes a segment of the most frequent economic indicators in the previous literature. With increasing emphasis on global environmental issues and the enhancement of ecological awareness, it was not surprising that environmental performance has become the essential assessment indicator for suppliers in the selection system [13,14,62–65]. Table 3 summarizes the environmental indicators that have been widely recognized and used in the past. Although the study on CSR has been not a new topic and has already borne fruit, research on integrating CSR (and also sustainability) with supplier selection has emerged only in recent years [63,66,67]. In reality, the internal stakeholders (such as shareholders) and external stakeholders (such as governments, local communities, non-governmental organizations, and consumers) in the supply chain are constantly putting social responsibility pressure on the firm itself [66,68]. Corporate behaviors and practices in terms of social responsibility, such as the voluntary integration of sustainable concerns into their commercial operations, influence all levels of the supply chain, but especially business partners [69]. Enterprises gradually recognized that their initiatives in SSCM will eventually exert an impact on their social image, reputation, and long-term benefits [70], and are responsible for the environmental, well-being, and security requirements of the laborers who manufacture their products, no matter whether they are direct employees or whether they come from the suppliers who provide them with raw materials or semi-finished products [71]. Table 4 provides some important sustainable criteria from the existing literature. Most authors have emphasized concern for employee responsibility, in the form of occupational health and safety [4,15–17,72], training and practice [15,18], and other legitimate rights [4,15]. The rights of stakeholders have also been recognized by many researchers [4,7,29,72], but the concept is more general because groups such as laborers, shareholders, governments, and so forth are all stakeholders of the company, and it is obviously not sufficient to describe rights using such an indicator. Information disclosure reveals the willingness of enterprises to fulfill their social responsibilities to some degree [4,29], but it is usually hard to measure performance by a single factor. Few papers pay attention to external stakeholders, except for their influence on the local community [73,74]; criteria like taxation, charitable investments, and shareholder contracts, are rarely included in the evaluation systems of sustainable suppliers. Nevertheless, the indicators proposed in the past three years, such as ethical and legal issues [17], discrimination and diversity [7], sustainability risks [57], supportive activities [16], and trust and partnerships [18], have some reference values. In general, the current social dimension for sustainable suppliers lacks the systematic consideration of responsibilities to internal and external stakeholders, focusing rather on only one or a few objects. This paper therefore attempts to establish a novel criteria framework of SSS for retail enterprises, especially those existing in the emerging economy whose SSCM initiatives got off to a late start.

2.3. The Measures

Through reviewing and combing through over 300 papers published from 2000 to 2017 (on the "topic, abstract and keywords" in regards to "sustainable supplier") from databases such as the Web of Science, Springer, Wiley, and Scopus, as well as in-depth consultations with experts in various industries, based on the TBL theory and stakeholder theory, a comprehensive measure for SSS in the retail industry was formulated. Given the trade-off between economic, environmental, and societal objectives, this measure covers six aspects (and a total of 24 sub-criteria), namely: Corporate Reputation (AS1), Operational Management (AS2), Product Advantage (AS3), Service Capability (AS4), Green Impact (AS5), and Social Responsibility (AS6). One of the most innovative parts among these aspects is the introduction of the main content of supplier social responsibility, which is not only reflected in suppliers' duties to internal stakeholders (such as employees and shareholders), but also to external stakeholders (such as community and the government). Among the sub-criteria, in addition to the reservation of some traditional, highly cited criteria such as procurement costs, financial status, product quality, supply flexibility, responsiveness, etc., we also considered other, new indicators according to corporate practices and expert opinion, including position in industry, contractual capacity, strategic alliance, learning, business process management, customer satisfaction, maintenance and compensation, governmental relations, and shareholder contracts; explanations are presented in Table 5. The proposed measure attempts to objectively reflect the actual capabilities and potential of alternative suppliers to maintain the long-term benefits of the supply chain through cooperation with partners.

Table 2. The economic supplier selection criteria.

Criteria	Explanations	Related Attributes	References
Cost/price	The final cost to purchase a unit of raw or semi-finished products.	Product cost, logistics cost, ordering cost, inventory cost, warranty cost, maintenance cost, manufacturing cost	[2,18,63,74–79]
Quality	The performance of materials purchased to meet or exceed the requirements and expectations in service or product that were committed to.	ISO quality system, product performance, warranties and claim policies, repair and return rate	[12,63,75,77,80,81]
Technology capability	The sum of all the knowledge of an enterprise in support of technological innovation.	Manufacturing facilities, informatization level for the enterprise, technological compatibility	[2,6,75,82,83]
Production capacity	The ability of human, financial, and material resources that is related to the product manufacturing.	New launch of products, supply capacity, product advantage, production facilities	[67,79,84]
Financial capability	The capital needed to maintain normal business activities for an enterprise during a certain period of time.	Financial position, debt ratio and current ratio, profit/sale trends, finance stability, interest on payment purchasing	[75,85–87]
Delivery	The capability of transporting goods from a source location to a predefined destination.	Lead time, on time, safety and security of components, delivery reliability	[21,74,77,79,88,89]
Service	The efficiency of scheduling and ability to handle changing orders, after-sales responsibility of suppliers, as well as motivation to share skills to solve problems.	Standard of service, punctuality, responsiveness, service capability, value added services to customers, information acquisition	[63,75,77,90,91]
Relationship	Determining the willingness to establish long-term and close business relations with suppliers to jointly develop the market.	Long term relationship, communication openness, reputation for integrity, relationship closeness	[64,81,82,92,93]
Flexibility	Demand that can be profitably sustained, and time or cost required to add new products to existing production operations.	Product volume changes, short set-up time, conflict resolution, using flexible machines	[18,64,81,82,91,94–96]

Table 3. The environmental supplier selection criteria.

Criteria	Explanations	Related Attributes	References
Green image	The identity that consumers prioritize environmental conservation and sustainable business practices.	Ratio of green customers to total customers, green customers market share, green materials coding and recording	[14,66,78,80,97–99]
Environmental management system	A system that comprehensively evaluates the internal and external environmental performance of an organization.	Environmental certificates such as ISO 14000, green process planning, regulatory compliance, environmental policies	[63,75,77,80,81,97,98]
Environmental competencies	The capacity to balance the containment relationships between economic and environmental performance for an enterprise.	Technical transformation ability, ability to change process and product for reducing the impact on natural resources, carbon footprint reduction	[14,50,66,80,97,100–102]
Pollution control	The control of pollutants that are released into air, water, or soil.	Remediation, end-of-pipe controls, air emissions, waste water, pollution control capability, pollution reduction capability	[66,74,78,97,99]

Table 3. *Cont.*

Criteria	Explanations	Related Attributes	References
Green product	Environmentally conscious products, which are pollution-free, resource-saving, or renewable and recyclable.	Use of recycled and nontoxic materials, green packaging, reuse, re-manufacture, disposal	[6,13,14,81,97]
Resource consumption	The use of non-renewable, or less often, renewable resources.	Consumption of resources in terms of raw material, energy, and water	[68,75,78,97]
ECO-design	An approach to designing products with special consideration for the environmental impacts of the product during its whole lifecycle.	Design for resource efficiency, design of products for reuse, recycle, and recovery of material, design for reduction or elimination of hazardous materials	[13,77,85,89,97,98,103]
GSCM	Considering environmental issues on supply chain; focusing the coordination between economy and environment.	Commitment of senior managers to support and improve green supply chain management initiatives, GSCM practice	[6,14,50,66,78,81,104,105]
Green technology innovation	The ability to continuously update environmental technologies to achieve the goal of minimizing the sum of product life cycle costs.	Green technology capabilities, recycling product design, renewable product design, redesign of product, green R&D project, green process	[66,77,78,99,105–107]

Table 4. The social supplier selection criteria.

Criteria	Explanations	Related Attributes	References
The rights of the employee	A group of legal rights and claimed human rights having to do with labor relations between workers and their employers.	Staff training on sustainable issues, equity labor sources, disciplinary and security practices, employee contracts	[6,16,18,63,85,99]
The rights of stakeholders	The right or welfare belonging to the person who holds the stake or some relevant interests in the private sector.	Partnership standards, share level, stakeholder empowerment, stakeholder engagement, consumers education,	[43,63,68,99,108]
Work safety and health	Concerned with the safety, health, and welfare of people at work.	Health and safety incidents, health and safety practices	[4,50,67,74,82,109]
Local community influence	Neighboring relations between the company and the local government, the community and all residents, representing the public image of the organization.	Service infrastructure, social pathologies, regulatory and public services, grants and donations, supporting community projects	[68,73,74]
Respect for the law and policy	Enterprises comply with all laws and regulations of the country, assume legal obligations, and promote good social public morals.	Regulatory and public services, ethical issues and legal complain, power	[17,63,77,99,110]
Staff Training	The process of enhancing the skills, capabilities, and knowledge of employees for a particular job.	Flexible working arrangements, job opportunities, career development	[15,18,66,68]
Information disclosure	Providing information to stakeholders about the materials used, carbon emissions, toxins released during production, and so on.	Transparency, information publicity, voluntary disclosure, public disclosure	[4,7,29,43,63]
Child and forced labor	The employment of children in any work that deprives them of their childhood and ability to attend regular school.	Child labor avoidance	[7]

Table 5. The measures of SSS.

Primary Criteria	Second Grade Criteria	Explanations	Reference/Basis
Corporate Reputation (CR)	Position in industry *	The market appeal, voice and dominant ability.	[111]
	Financial status	Funds-collection and application within a certain period, reflecting whether the capital flow is smooth.	[75,85]
	Contractual capacity *	The actual ability to perform economic contracts.	[112]
	Strategic alliance *	The compatibility of long-term strategies and plans.	[113]
Operational Management (OM)	Business process management *	The ability to coordinate logistics, business, and information flow, and to discover, analyze, optimize, and automate business processes.	[114,115]
	Technical support	The ability to use computer and network technology to make decisions.	[75,82]
	Quality management	Through quality planning, control, assurance and improvement to ensure product consistency.	[12,99]
	Learning * and Innovation	Through learning to enable firms to make continuous innovations, and improve their ability to adapt to the change.	[18,75]
Product Advantage (PA)	Procurement cost	Constituted by the purchase price and the costs incurred for the purchase of goods.	[91,99]
	Product quality	The embodiment of the use value of products, including the intrinsic quality and appearance quality.	[90]
	Supply flexibility	The ability to quickly respond to different product demands.	[101]
	Product market share	The proportion of a company's sales volume (or sales profit) in the market.	[112,116]
Service Capability (SC)	Responsiveness	The ability to quickly identify, react to, and recover from the changes.	[99]
	Timely delivery	The ability to deliver goods on time, usually expressed on a timely delivery rate.	[88,99]
	Customer satisfaction *	How the products and services supplied by a company meet or surpass customer expectation.	[110,116]
	Maintenance and Compensation *	The after-sales service ability for defective products or equipment, including recall.	[16,18]
Green Impact (GI)	Pollution production	Environmental pollution caused by the production of products.	[104,117]
	Pollution control	Control and reduce the pollution caused by the production process.	[99]
	Energy consumption	The consumption of energy or power produced in the production.	[75,118]
	Ecologic design	Consideration of the environmental impact of the entire product life cycle at the design stage.	[85]
Social Responsibility (SR)	Labor relations record	Historic records revealing the relationship between labor and enterprise.	[99]
	Governmental relations *	The ability of an enterprise to be trusted, supported, and cooperated with the government	[110]
	Community welfare investment	Charity and welfare services to local communities.	[74]
	Shareholder contract *	Safeguarding the interests of shareholders and bringing value to the shareholders.	[119]

The symbol * represents the new indicator.

2.4. Supplier Selection Methods

Approaches to supplier selection have gone through three main stages of evolution [120]. Early studies on supplier selection normally adopted qualitative methods such as the Heuristics of Judgment, Bidding, and Consultation Choice [121]. However, due to the overdependence on the subjective judgment of DMs, this type of method was less accepted by subsequent procurement managers. They instead tried to use quantitative methods, such as the Entropy method, to get easy access to the relative weights of the criteria for ranking their suppliers [122]. Nonetheless, authors later found that many criteria, like "strategic alliance" and "innovation intention", could not be directly quantified. Though some of their sub-criteria may be quantifiable, they could not entirely represent or replace the concepts of the original criteria. Combination methods (quantitative and qualitative) have, therefore, appeared and become the mainstream in field of supplier selection. Currently, models and methods that were applied generally include the following four categories: (a) MCDM methods (for example, AHP, ANP, TOPSIS, VIKOR, and so forth); (b) Mathematical Programming (MP) models (for example, DEA, Linear Programming (LP), Nonlinear Programming (NLP), Multi-objective Programming (MOP), and so forth); (c) Artificial Intelligence Technology (AIT) (for example, Grey Relation Analysis (GRA), ANN, Case-based Reasoning (CBR), Decision Support Systems (DSS), and so forth); and (d) Other Hybrid Models which are basically an integration of the above methods that assembled unique advantages of each technique and provided more sophisticated structures to assess supplier performance [7,123]. Moreover, from fuzzy set theory, introducing fuzzy numbers with various forms to characterize the uncertainty of information is also quite commonly adopted in this field [124]. Table 6 shows the diverse extended forms of typical portfolio models used in the supplier selection area.

Table 6. The typical extended methods for supplier selection.

Methods	Extension	Forms	References
AHP	Fuzzy AHP	Fuzzy AHP	[77,125,126]
	Integrated AHP	AHP and ANN	[127]
		AHP and GA [1]	[128]
		AHP and DEA	[129]
		AHP and GRA	[130]
		AHP and MP	[126]
		AHP and Fuzzy TOPSIS	[16,131,132]
		AHP and VIKOR	[29]
		AHP and Entropy and TOPSIS	[49]
ANP	Fuzzy ANP	Fuzzy ANP	[6,133]
	Integrated ANP	ANP and DEA	[134]
		ANP and QFD [2]	[17]
		ANP and IPA [3]	[135]
		ANP and RST [4]	[104]
		ANP and PROMETHEE	[136]
		ANP and VIKOR	[137]
		ANP and LP	[138]
		DEMATEL	[139,140]
		TOPSIS	[141]
		Fuzzy ANP and SWOT [5]	[142]
DEA	Fuzzy DEA	Fuzzy DEA	[100,143]
		DEA and ANN	[144]
		DEA, ANP and ANN	[63]
		DEA and MOLP [6]	[100]
		DEA and RST	[5]
		DEA and DE [7] and MODE [8]	[30]
GRA	Fuzzy GRA	Fuzzy GRA	[103]
	Integrated GRA	GRA and AHP	[145]
		GRA and ANP	[2,146]
		GS [9] and RST	[50]
		GRA and DEMATEL	[147,148]
TOPSIS	Fuzzy TOPSIS	Fuzzy TOPSIS	[65,66,68,149]
	Integrated TOPSIS	DEMATEL-ANP-TOPSIS	[76]
		TOPSIS and ANN	[72]

Table 6. *Cont.*

Methods	Extension	Forms	References
VIKOR	Fuzzy VIKOR	Fuzzy VIKOR	[25]
	Integrated VIKOR	VIKOR and AHP	[29]
		VIKOR and NGT [10]	[109]
		VIKOR and fuzzy ELECTRE	[150]

[1] GA: Genetic Algorithm; [2] QFD: Quality Function Deployment; [3] IPA: Importance Performance Analysis; [4] RST: Rough Set Theory; [5] SWOT: Superiority Weakness Opportunity Threats; [6] MOLP: Multiple Objective Linear Programming; [7] DE: Differential Evolution; [8] MODE: Multi-objective Differential Evolution; [9] GS: Grey System; [10] NGT: Nominal Group Technique.

MCDM, a centralized decision-making method for ranking and choosing the optimal alternative in limited (infinite) programs under a conflicting and non-commensurable situation, has wide applications in many fields, including engineering, military, economy, technology, and management [5,6,72]. In the multiple criteria framework for supplier selection, single-goal methods would hardly solve the problem, as cost indicators and benefit indicators are often contradictory. MCDM methods such as the TOPSIS and VIKOR techniques, relying on consolidation function measuring the "closeness to the ideal solution", are proved to be typical compromise programming technologies [24,151] which can logically and effectively address SSS issues with multiple objectives. Compared with a large number of the extensions of the TOPSIS method in the past decade, the improved forms of the VIKOR algorithm have just appeared in recent years. However, VIKOR is technically superior to TOPSIS, mainly because the final optimal solution obtained by VIKOR is closer to the ideal solution than that of TOPSIS [24].

Before using the VIKOR algorithm to acquire priority ranking, criteria weights need to be determined first. Expert experience and the weighted average method are universally used in reality [28], but such methods barely consider possible judgment biases that DMs may make, and rarely inspect any potential inconsistencies within the model [12]. The AHP, ANP, and ANN methods have been applied to address such limitations; however, these methods assume that indicators are internally independent, and therefore, ignore the possible interdependencies among them [49,63], which may yield erroneous weights. As the relationships between calculated weights can deviate from the actual phenomenon, scholars for this concern have considered combining the DEMATEL method with the ANP to calculate weights [28,76,152]. DEMATEL can analyze the interplay among the evaluation indexes and obtain a more intuitive index network structure which may help to redefine the relationship between the first-and second-level indexes under ANP, so as to acquire more accurate and objective criteria weights. This weight acquisition approach has seldom been applied in SSS, and existing studies almost always stop at the combination of the DEMATEL, ANP and VIKOR methods, rarely expanding further.

On the other hand, as the input of VIKOR, the value of indicators is not always easy to observe directly due to the complexity and uncertainty of the SSS problem. Fuzzy number is therefore introduced to be an effective extension to characterize the vagueness and uncertainty in the data process [81]. Interval number [152,153], triangular fuzzy number [25,154], trapezoidal fuzzy number [12], intuitionistic fuzzy number [155], two-tuple linguistic information [156], generalized interval trapezoidal fuzzy number [157], and other different forms of fuzzy number have been widely applied to be information aggregation under the VIKOR method, but there are hardly any applications introducing IVTFN into the VIKOR method, and this fuzzy number is seldom used to describe the characteristics of indicators for sustainable suppliers. As Kuo and Liang [27] and Lin and Tseng [26] have verified the applicability and effectiveness of the IVTFN in performance evaluation, we thereby consider introducing this data type into the SSS problem as the semantic expression of qualitative indicators.

3. Methodology

An improved integrated MCDM model with hybrid information aggregation for SSS has been proposed; it includes four phases. The first phase involves identification of the criteria used to evaluate the social performance of suppliers. In this study, the measure is determined from both literature reviews and discussions with the experts in the industry, especially retailing. After that, it integrates the DEMATEL method to examine the interrelationships between the indicators with the ANP method to calculate the criteria weights. In the third stage, hybrid data type is introduced to describe quantitative and qualitative criteria of candidate suppliers to the aggregate hybrid information set for subsequent decision. In the final phase, the VIKOR method is adopted to rank and determine the optimal sustainable supplier according to the mixed information set, while a sensitivity analysis is conducted to test the robustness of the proposed model. The technical route of the integrated method is shown in Figure 2.

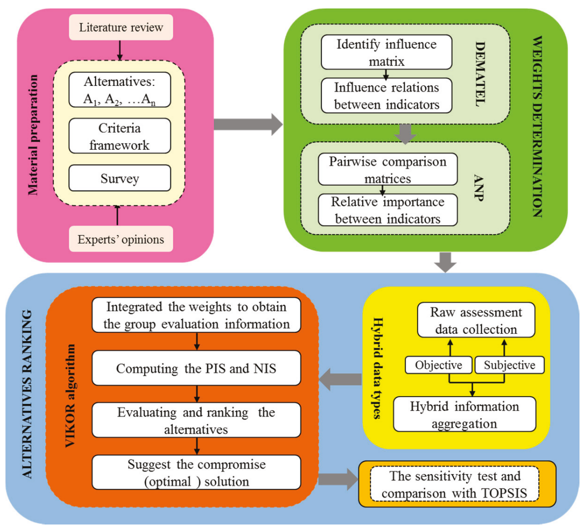

Figure 2. The proposed integrated hybrid-valued MCDM model for a sustainable supplier.

3.1. DEMATEL-ANP-VIKOR

3.1.1. Combining the DEMATEL and ANP to Obtain Criteria Weights

The ANP is the general form of AHP proposed by Saaty [158], which considers the inter-dependency and relationship between the factors group in a super-matrix way, and can calculate the criteria weights in the network structure through a systematic decision process which reflects the logical relationship of the factors. However, Ou Yang, Shieh, Leu and Tzeng [20] pointed out that the weight of each cluster should not be equal in obtaining a weighted super-matrix, because this method ignores the prior consideration of the interrelationship between factors. Then, the DEMATEL, a method that is increasingly being applied to identify the potential interrelationships among factors and to analyze strong or weak correlations based on the graph theory and matrix tools [159], is considered in combintation with ANP in weight determination. An empirical study indicates the effectiveness of this integrated method [20,76,160], which employs the DEMATEL method to calculate the degree of impact between the indicators before determining the relative importance among the criteria in ANP. Based on this logic, we further improve the DEMATEL-ANP method by simplifying the process of obtaining a network relationships map of influence, which not only does not change the results, but can effectively reduce the amount of calculation. The process of the DEMATEL-ANP algorithm is as follows [161,162]:

- Step 1: Calculating the initial average matrix through expert marks. Given the integer scale from 0 to 4 ("No impact (0)", "Low impact (1)", "Moderate impact (2)", "High impact (3)", and "Super-high impact (4)", respectively), inviting experts to answer the direct effects that they think criterion i imposed on another criterion j, as indicated by a_{ij}. We can obtain an average matrix $A = [a_{ij}]_{n\times n}$ by any direct matrix set, of which factors in matrix A are the mean values integrated from the initial experts' judgments.
- Step 2: Deriving the full direct/indirect impact matrix and normalizing the direct impact matrix D, as shown in Equation (1).

$$\begin{aligned} &D = k \times A, where \\ &k = \min\left(\frac{1}{\max_{1\le i\le n}\sum_{j=1}^{n}|a_{ij}|}, \frac{1}{\max_{1\le j\le n}\sum_{i=1}^{n}|a_{ij}|}\right) \end{aligned} \tag{1}$$

- Step 3: Obtaining the total impact matrix T through Equation (2); I represents the identity matrix.

$$T = D^1 + D^2 + D^3 + \cdots = \sum_{i=1}^{+\infty} D^i = D\cdot(I-D)^{-1} \tag{2}$$

- Step 4: Defining the sum of rows and sums of columns, respectively, as vectors R and C in the total impact matrix T via Equations (3)–(5), of which element (i,j) can be denoted as t_{ij}, and

$$T = (t_{ij})_{n\times n}, i, j \in \{1, 2, \cdots, n\} \tag{3}$$

$$R = \sum_{j=1}^{n} t_{ij} \tag{4}$$

$$C = \sum_{i=1}^{n} t_{ij} \tag{5}$$

Notably, $(c_i + r_i)$ is donated as the center degree which represents the relative importance of factor i while $(c_i - r_i)$ is denoted as the cause degree, indicating the relationship between factor i and the others. If $(c_i - r_i)$ is positive, then factor i affects the other factors. Otherwise, it is corrupted by other effects [163–165].

- Step 5: Generating a causal diagram of the primary index to identify the relationship between the primary indicators and their importance according to the value of center degree $(c_i + r_i)$ and cause degree $(c_i - r_i)$.
- Step 6: Identifying the relationship between the primary indicators according to the DEMATEL method, setting the thresholds [162], and removing the indicators with a weaker impact, re-determining the incidence relation between the indicators, and drawing the influence relation diagram while combining it with the actual situation of the secondary indicators to map the ANP network structure.
- Step 7: Constructing judgment matrix W, assuming that in the network structure of ANP the indicators for the goal G in the control layer are indicated as $S_1, S_2, S_3, \cdots, S_m$ while the element set in the network layer is indicated as $C_1, C_2, C_3, \cdots, C_n$, where elements $c_{i1}, c_{i2}, c_{i3}, \cdots, c_{in} (i = 1, 2, \cdots n)$ are in C_i. Regarding S_i in the control layer as the indicator, and c_{jk} in C_j as the sub-criteria, and comparing the degree of impact c_{jk} influenced by the other elements in C_i, allows for the construction of the judgment matrix under the indicator S_i. On this basis, the normalized feature vector $W_{i1}^{(jk)}, W_{i2}^{(jk)}, \cdots W_{in}^{(jk)}$ can be calculated as the ordering vector of the

network element. By repeating the above steps for $k = 1, 2, \cdots, n_i$, the following matrix can be obtained by Equation (6).

$$W_{ij} = \begin{Bmatrix} W_{i1}^{(j1)} & \cdots & W_{i1}^{(jn_j)} \\ \vdots & & \vdots \\ W_{in_1}^{(j1)} & \cdots & W_{in_1}^{(jn_j)} \end{Bmatrix} \tag{6}$$

- Step 8: Contributing to pairwise comparisons. According to the structure of the judgment matrix W, the relative importance of the clusters and factors forming the ANP decision network is obtained through expert pairwise comparisons. The relative importance of the calculated factors is attained by comparing the results of the individual indicators [146].
- Step 9: Solving the unweighted super-matrix, the weighted super-matrix, and the limit super-matrix. By combining with the interactional ordering vector of all network layer elements to form a super-matrix $\widetilde{W}$ under the control element S_i and normalizing each column, we can then obtain the weight matrix E, which is composed of the ordering vectors. As is shown in Equation (7), e_{ij} represents the influence weight of element group i on group j under the criterion S_i in the control layer. If these two factors have no impact on each other, then $e_{ij} = 0$. The resulting weighted super-matrix, as shown in Equation (8), is the sum of the elements of each column equal to 1. Then, we make a stability process for the weighted super-matrix to calculate the limit relative ordering vector $\lim_{k \to +\infty} \overline{W}^k$. If this limit is convergent and unique, then the column i is the ranking of the element i relative to the other elements in the network layer under the criterion, namely, the weight value of each element relative to the highest target.

$$E = \begin{pmatrix} e_{i1} & \cdots & e_{i1} \\ \vdots & & \vdots \\ e_{in_i} & \cdots & e_{in_i} \end{pmatrix} \tag{7}$$

$$\overline{W} = E \times \widetilde{W} = (\overline{W}_{ij}) = (e_{ij} \times \widetilde{W}_{ij}) \tag{8}$$

3.1.2. Ranking Candidate Suppliers Using the VIKOR Technique

The Algorithm Principle of VIKOR and Comparison with TOPSIS

The VIKOR technique is a MCDM method proposed by Opricovic in 1998, which both considers maximizing the group benefit and minimizing the individual regret of the opposition [151] to solve the optimal compromise solution. Compared with another typical MCDM method, TOPSIS, which defines that the optimal solution should be the shortest distance from the positive ideal solution (PIS) and the longest distance from the negative ideal solution (NIS) [65], VIKOR uses the group-decision consolidation function Q to measure the distance between the potential and the ideal solutions. TOPSIS determines the final rankings through the calculation of the aggregate function $\varepsilon_i = d^- / (d^- + d^+)$, while d^- and d^+ represent the distance from the NIS and PIS, respectively. However, this function has a theoretical limitation that the final scheme obtained is not always the closest to the ideal solution. We illustrate this further in Figure 3. Assuming that the distance between A_k and the NIS is the same as that of PIS (that is, $d^+ = d^-$), for any alternative A_i, it will always prevail over A_k, as long as it satisfies the requirement that the distance to the NIS be longer than to the PIS (that is, $d^- > d^+$) for $\varepsilon_i = \frac{d^-}{d^- + d^+} > 0.5 = \varepsilon_k$. Even though the scheme is closer to the PIS (that is, $d_k^+ > d_i^+$), the priority position will not change under the TOPSIS method.

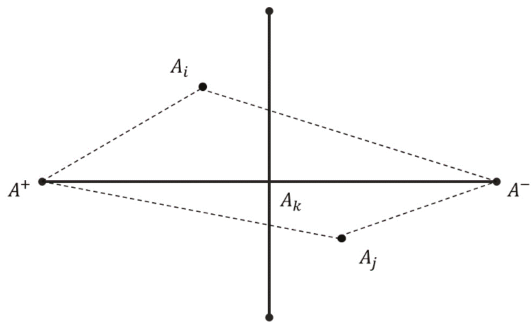

Figure 3. The distance measurement of TOPSIS.

In addition, the location of PIS and NIS are of importance to the actual decision, but the TOPSIS method cannot observe the relative importance between the alternatives and these two points [24]. In short, the TOPSIS method is more suitable for solving the risk decision problem, while the VIKOR scheme is applicable to those DMs that tend to maximize team effectiveness. Since the choice of sustainable suppliers needs to consider the comprehensive benefits from the economic, environmental, and societal aspects, the VIKOR algorithm is better-suited.

The Computational Procedure of VIKOR

- Step 1: Assembling and transforming the original quantitative data based on transaction records, market performances, and the qualitative information judged by the scorers, integrating the weights obtained through the DEMATEL-ANP method to get the group evaluation information, and further build a streamlined fuzzy evaluation matrix, as shown in Equations (9) and (10) for the weight.

$$X = \begin{pmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{1n} \\ \vdots & & \vdots \\ \widetilde{x}_{m1} & \cdots & \widetilde{x}_{mn} \end{pmatrix} = [\widetilde{x}_{ij}]_{m \times n} \quad (9)$$

$$w = [\widetilde{w}_1, \widetilde{w}_2, \cdots, \widetilde{w}_n], \widetilde{w}_i \geq 0 \quad (10)$$

where $\widetilde{x}_{ij}$ represents the performance of c_j under alternative A_i, $i = 1, 2, \cdots, m$, $j = 1, 2, \cdots, n$. w_j represents the weight of c_j as determined by the DEMATEL-ANP method.

Considering the different importance level of each criterion c_j, and constructing the weighted interval decision fuzzy matrix, $\widetilde{V} = [\widetilde{v}_{ij}]$, where $\widetilde{v}_{ij} = \widetilde{x}_{ij}(\cdot)\widetilde{w}_j = [(a_{ij}, a'_{ij}), b_{ij}, (c_{ij}, c'_{ij})]$, $i = 1, 2, \cdots, m$; $j = 1, 2, \cdots, n$.

- Step 2: After determining the decision matrix, the PISs (A^{*1} and A^{*2}) and NIS (A^{-1}) can be attained, as shown in Equations (11)–(13), where B represents the beneficial criteria and C represents the cost criteria.

$$\begin{gathered} A^{*1} = \{\widetilde{x}_1^*, \widetilde{x}_2^*, \cdots, \widetilde{x}_n^*\} = \{(\max_i \widetilde{x}_{ij} | j \in B) or (\min_i \widetilde{x}_{ij} | j \in C)\} \\ j = 1, 2, \cdots, n = \{[(l_1^*, l'^*_1), m_1^*, (r'^*_1, r_1^*)], [(l_2^*, l'^*_2), m_2^*, (r'^*_2, r_2^*)], \cdots, [(l_n^*, l'^*_n), m_n^*, (r'^*_n, r_n^*)]\} \end{gathered} \quad (11)$$

$$\begin{gathered} A^{*2} = \{\widetilde{v}_1^*, \widetilde{v}_2^*, \cdots, \widetilde{v}_n^*\} = \{(\max_i \widetilde{v}_{ij} | j \in B) or (\min_i \widetilde{v}_{ij} | j \in C)\} \\ j = 1, 2, \cdots, n = \{[(a_1^*, a'^*_1), b_1^*, (c'^*_1, c_1^*)], [(a_2^*, a'^*_2), b_2^*, (c'^*_2, c_2^*)], \cdots, [(a_n^*, a'^*_n), b_n^*, (c'^*_n, c_n^*)]\} \end{gathered} \quad (12)$$

$$\begin{gathered} A^{-1} = \{\widetilde{x}_1^-, \widetilde{x}_2^-, \cdots, \widetilde{x}_n^-\} = \{(\min_i \widetilde{x}_{ij} | j \in B) or (\max_i \widetilde{x}_{ij} | j \in C)\} \\ j = 1, 2, \cdots, n = \left\{[(l_1^-, l'^-_1), m_1^-, (r'^-_1, r_1^-)], [(l_2^-, l'^-_2), m_2^-, (r'^-_2, r_2^-)], \cdots, [(l_n^-, l'^-_n), m_n^-, (r'^-_n, r_n^-)]\right\} \end{gathered} \quad (13)$$

- Step 3: Following Equations (14)–(17) to obtain the $\widetilde{S}_i$ and $\widetilde{R}_i$ values of the potential supplier, respectively:

$$\widetilde{S}_i = \sum_{j=1}^{n} \left(\frac{\widetilde{s}_{ij}^{U} + \widetilde{s}_{ij}^{L}}{2}\right) \tag{14}$$

$$\widetilde{R}_i = \max_j\left(\frac{\widetilde{s}_{ij}^{U} + \widetilde{s}_{ij}^{L}}{2}\right), i = 1, 2, \cdots, m \tag{15}$$

$$\widetilde{s}_{ij}^{U} = \sum_{j\in B} \frac{\sqrt{\frac{1}{3}[(a_j^* - a_j)^2 + (b_j^* - b_j)^2 + (c_j^* - c_j)^2]}}{\sqrt{\frac{1}{3}[(l_j^* - l_j^-)^2 + (m_j^* - m_j^-)^2 + (r_j^* - r_j^-)^2]}} + \sum_{j\in C} \frac{\sqrt{\frac{1}{3}[(a_j - a_j^*)^2 + (b_j - b_j^*)^2 + (c_j - c_j^*)^2]}}{\sqrt{\frac{1}{3}[(l_j^- - l_j^*)^2 + (m_j^- - m_j^*)^2 + (r_j^- - r_j^*)^2]}} \tag{16}$$

$$\widetilde{s}_{ij}^{L} = \sum_{j\in B} \frac{\sqrt{\frac{1}{3}[(a'^*_j - a'_j)^2 + (b_j^* - b_j)^2 + (c'^*_j - c'_j)^2]}}{\sqrt{\frac{1}{3}[(l'^*_j - l'^-_j)^2 + (m'^*_j - m'^-_j)^2 + (r'^*_j - r'^-_j)^2]}} + \sum_{j\in C} \frac{\sqrt{\frac{1}{3}[(a'_j - a'^*_j)^2 + (b_j - b_j^*)^2 + (c'_j - c'^*_j)^2]}}{\sqrt{\frac{1}{3}[(l'^-_j - l'^*_j)^2 + (m'^-_j - m'^*_j)^2 + (r'^-_j - r'^*_j)^2]}} \tag{17}$$

- Step 4: Acquiring the corresponding $\widetilde{Q}_i$ basis of $\widetilde{S}_i$ and $\widetilde{R}_i$ through Equation (18):

$$\widetilde{Q}_j = v(\widetilde{S}_j - \widetilde{S}^*)/(\widetilde{S}^- - \widetilde{S}^*) + (1 - v)(\widetilde{R}_j - \widetilde{R}^*)/(\widetilde{R}^- - \widetilde{R}^*) \tag{18}$$

where $\widetilde{S}^* = \min_j \widetilde{S}_j; \widetilde{S}^- = \max_j \widetilde{S}_j; \widetilde{R}^* = \min_j \widetilde{R}_j; \widetilde{R}^- = \max_j \widetilde{R}_j$.

In equation (18), v represents the decision mechanism coefficient. When (1) v is greater than 0.5, the final decision is made by most people; (2) when v is approximately equal to 0.5, the final decision is made with actual approval; and (3) when v is smaller than 0.5, the final decision is made by fewer people. Generally, it is assumed that v equals 0.5 for pursuing the maximization of group utility and minimizing the individual regrets in the VIKOR method.

- Step 5: Obtaining the ranks of the alternatives according to the value of $\widetilde{Q}_j$, $\widetilde{S}_j$ and $\widetilde{R}_j$ respectively. Notably, the smaller the $\widetilde{Q}_j$ value is, the better the scheme may be.
- Step 6: After determining the sorting scheme, checking whether the compromise can be accepted. If the following two conditions are met, the compromise solution according to the $\widetilde{Q}_j$ value will be the best alternative.

Condition 1. *If $Q(A^{(2)} - A^{(1)}) \geq DQ$, where $DQ = 1/(J-1)$, J represents the quantity of candidate suppliers and $A^{(1)}$ and $A^{(2)}$ are the ranking first and second alternatives in ascending order according to the Q value, that is, $Q(A^{(2)})$ is expressed as the second minimum Q and $Q(A^{(1)})$ is expressed as the first minimum Q, then the corresponding option for $Q(A^{(1)})$ (with a minimum Q value) will be the optimal solution or the compromise.*

Condition 2. *Alternatives $Q(A^{(1)})$ must both satisfy the optimal order by S and/or R values in ascending order.*

If one of the above conditions is not satisfied, then only a set of compromise schemes can be obtained, namely,

1. If Condition 2 is not met, the final set contains $A^{(1)}$ and $A^{(2)}$;
2. If Condition 1 is not met, the final set contains $A^{(1)}, A^{(2)}, \cdots, A^{(L)}$, where the maximum value of L in $A^{(L)}$ is decided by $Q(A^{(L)} - A^{(1)}) < DQ$.

3.2. Hybrid Data Type and Information Aggregation

Since qualitative factors and quantitative indicators often coexist simultaneously in the measure of supplier selection, it cannot be accurate and in line with reality if those factors are scored by a single value type. This paper proposes hybrid information aggregation which can reduce the vague and subjective impact of human judgments and preferences through mixed data forms to describe the comprehensive performance of potential suppliers, which includes the precise number, interval number, and fuzzy number.

3.2.1. Precise Number

The economic assessment criteria of a sustainable supplier like cost, price, and order response rate can be characterized as precise numbers in line with market performance and transaction records. For the numeric data h_{ij}, we use Equation (19) to eliminate the effects of the dimension through a normalization procedure, and then donated r_{ij} after the processing in which B and C are express as the beneficial indicator and cost indicator, separately.

$$r_{ij} = \begin{cases} \frac{h_{ij}}{\max_j h_{ij}}, 1 \le i \le m, 1 \le j \le n, h_{ij} \in B \\ \frac{\min_j h_{ij}}{h_{ij}}, 1 \le i \le m, 1 \le j \le n, h_{ij} \in C \end{cases} \tag{19}$$

3.2.2. Interval Number

The interval number is able to depict the uncertainty of the quantitative data in the decision-making process. Through setting the interval, some quantitative indicators that do not have an accurate value can be measured. The distance measure for any two intervals can be defined as follows:

Definition 1. *For any two interval numbers $\widetilde{Y}_1 = [\widetilde{Y}_1{}^l, \widetilde{Y}_1{}^u]$ and $\widetilde{Y}_2 = [\widetilde{Y}_2{}^l, \widetilde{Y}_2{}^u]$, the distance can be calculated using Equation (20).*

$$d(\widetilde{Y}_1, \widetilde{Y}_2) = \frac{\sqrt{2}}{2}\sqrt{(\widetilde{Y}_1{}^l - \widetilde{Y}_2{}^l)^2 + (\widetilde{Y}_1{}^u - \widetilde{Y}_2{}^u)^2} \tag{20}$$

The interval number $[y_{ij}^l, y_{ij}^u]$ can be donated as $[r_{ij}^l, r_{ij}^u]$ after standardized processing while

$$\begin{array}{l} r_{ij}^l = \frac{y_{ij}^l}{\max_j x_{ij}^u}, r_{ij}^l = \frac{y_{ij}^u}{\max_j x_{ij}^u}, 1 \le i \le m, 1 \le j \le n, [y_{ij}^l, y_{ij}^u] \in B \\ r_{ij}^u = \frac{\min_j y_{ij}^l}{y_{ij}^u}, r_{ij}^l = \frac{\min_j y_{ij}^l}{y_{ij}^l}, 1 \le i \le m, 1 \le j \le n, [y_{ij}^l, y_{ij}^u] \in C \end{array} \tag{21}$$

3.2.3. Interval-Valued Triangular Fuzzy Number

Definition and Graphic Demonstration

Consider an MCDM problem, let $A = \{A_1, A_2, \cdots, A_m\}$ be a finite set of feasible alternatives and $C = \{C_1, C_2, \cdots, C_n\}$ be a finite set of criteria. The vector of the criteria weights $w = \{w_1, w_2, \cdots, w_n\}$ is unknown, but it satisfies $w_j \ge 0, j = 1, 2, \cdots, n, \sum_{j=1}^{n} w_j = 1$.

Definition 2. *Assuming that the performance of alternative A_i regarding any item of evaluation criteria C_j is defined as $\widetilde{X}_{ij}$, and $\widetilde{X}_{ij} = [\widetilde{x}_{ij}]_{m \times n}$ is a fuzzy matrix that contains the major evaluating qualitative factors, we define $\widetilde{x}_{ij}$ as an interval-valued triangular fuzzy number (IVTFN) [166], as shown in Figure 4.*

$$\widetilde{x} = \begin{cases} (x_1, x_2, x_3) \\ (x'_1, x_2, x'_3) \end{cases}, 0 < x_1 \le x' \le x_2 \le x'_3 \le x_3 \tag{22}$$

Then $\widetilde{x}_{ij}$ can be also demonstrated as $\widetilde{x} = [(x_1, x'_1); x_2; (x'_3, x_3)]$.

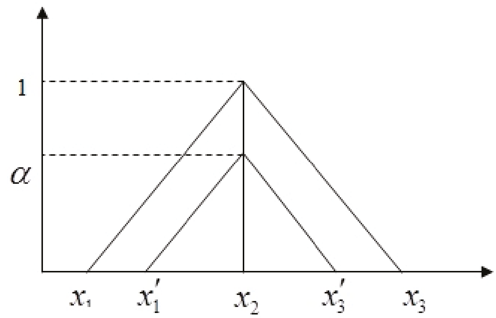

Figure 4. The diagram form of IVTFNs [166].

Arithmetic Operations

According to Definition 2, we can define two IVTFNs as $\tilde{x} = [(x_1, x'_1); x_2; (x'_3, x_3)]$ and $\tilde{y} = [(y_1, y'_1); y_2; (y'_3, y_3)]$, separately. Then the arithmetic rules for these two IVTFNs are represented as follows [166]:

(1) Addition:

$$\tilde{x} + \tilde{y} = [(x_1, x'_1); x_2; (x'_3, x_3)] + [(y_1, y'_1); y_2; (y'_3, y_3)] = [(x_1 + y_1, x'_1 + y'_1); x_2 + y_2; (x'_3 + y'_3, x_3 + y_3)] \quad (23)$$

(2) Subtraction:

$$\tilde{x} - \tilde{y} = [(x_1, x'_1); x_2; (x'_3, x_3)] - [(y_1, y'_1); y_2; (y'_3, y_3)] = [(x_1 - y_1, x'_1 - y'_1); x_2 - y_2; (x'_3 - y'_3, x_3 - y_3)] \quad (24)$$

(3) Multiplication:

$$\tilde{x} \otimes \tilde{y} = [(x_1, x'_1); x_2; (x'_3, x_3)] \otimes [(y_1, y'_1); y_2; (y'_3, y_3)] = [(x_1 y_1, x'_1 y'_1); x_2 y_2; (x'_3 y'_3, x_3 y_3)] \quad (25)$$

(4) Multiplication figure with IVTFNs:

$$k \times \tilde{x} = \left[\left(kx_1, kx'_1 \right); kx_2; \left(kx'_3, kx_3 \right) \right], \quad (26)$$

where k is an arbitrary positive real number.

(5) Reciprocal value:

$$\frac{1}{\tilde{x}} = \left[\left(\frac{1}{x_3}, \frac{1}{x'_3} \right); \frac{1}{x_2}; \left(\frac{1}{x'_1}, \frac{1}{x_1} \right) \right] \quad (27)$$

Distance Measure

Definition 3. *Suppose $\tilde{X} = [X^L, X^U]$ and $\tilde{Y} = [Y^L, Y^U]$ are two arbitrary IVTFNs, the normalized Euclidean distance can be calculated as follows [27]:*

$$d(\tilde{X}, \tilde{Y}) = \sqrt{\frac{1}{6} \sum_{x,y=1}^{3} [(\tilde{X}^L - \tilde{Y}^L)^2 + (\tilde{X}^U - \tilde{Y}^U)^2]} \quad (28)$$

$$d(\tilde{X}, \tilde{Y})^L = \sqrt{\frac{1}{3} \sum_{x,y=1}^{3} [(\tilde{X}^L - \tilde{Y}^L)^2]} \quad (29)$$

$$d(\tilde{X}, \tilde{Y})^U = \sqrt{\frac{1}{3} \sum_{x,y=1}^{3} [(\tilde{X}^U - \tilde{Y}^U)^2]} \quad (30)$$

Definition 4. *Let* $\widetilde{O} = [(0,0);0;(0,0)]$ *be an initial solution. Considering any two IVTFNs,* $\widetilde{X}$ *and* $\widetilde{Y}$*, If* $d(\widetilde{X},\widetilde{O}) < d(\widetilde{Y},\widetilde{O})$*, then* $\widetilde{X}$ *is closer to the initial solution than* $\widetilde{Y}$ *[27,167].*

Date Processing of Linguistic Variables

Linguistic terms are expressed in the form of natural language phrases; such simple and understandable terms can be used by DMs who have the subjective intentions to make qualitative judgments for the alternatives. Semantic variable types are normally transformed into triangular fuzzy numbers or intuitionistic fuzzy numbers, and the transformation standards are unified [166]. This paper transforms the partial semantic variables into IVTFNs, while the evaluation scale and the corresponding value of IVTFNs are shown in Table 7.

Table 7. The linguistic terms for rating the alternatives.

Linguistic Preference	Abbreviation	IVTFNs
Very poor	VP	(0, 0, 0, 1, 1.5)
Poor	P	(0, 0.5, 1, 2.5, 3.5)
Moderately poor	MP	(0, 1.5, 3, 4.5, 5.5)
Fair	F	(2.5, 3.5, 5, 6.5, 7.5)
Moderately good	MG	(4.5, 5.5, 7, 8, 9.5)
Good	G	(5.5, 7.5, 9, 9.5, 10)
Very good	VG	(8.5, 9.5, 10, 10, 10)

4. The Empirical Case of a Retail Enterprise

An empirical case study of SSS for a retail company is discussed in this section to illustrate the applicability and feasibility of the proposed measure and methodology. In the following chapter, we will discuss the background, data collection, and the evaluation processes respectively.

4.1. Background and Problem Descriptions

Sustainability in the supply chain is viewed by many as essential to delivering long-term profitability; this is particularly true for retail sector. Before 2016, some international retail giants such as Wal-Mart, Migros, and Hy-Vee successively called for the full procurement of sustainable marine food products. The Chinese government suggested that the large-scale retail supermarkets in China begin with a pilot implementation of sustainable seafood procurement plans; the FX Supermarket chain was among them. Founded in 2000, FX Supermarket is one of the first circulation enterprises and agricultural industrialization enterprises in China that introduced fresh products into modern supermarkets, focusing on agro-food, daily necessities, clothing, and so forth. After years of entrepreneurship and rapid development, FX has grown into one of largest commercial enterprises, with more than 300 large and medium-sized supermarket branches, an annual turnover of almost $10 billion, and 60,000 employees. FX has mastered the advantages of the upstream supply chain, of which fresh food is its biggest feature; the fresh produce area of each store has reached over 40 percent, and fresh agricultural and sideline products account for more than 50 percent of the total sales in the group.

For FX Supermarket, as they did not pre-determine the measure and corresponding method for sustainable suppliers of seafood (in fact, their previous procurement standards only focus on several traditional indicators such as cost, logistics, certification, and so forth, and some assessment methods they used were mainly experience-based judgment or weighted average), they finally contacted us to help them study this issue. Due to the different types of seafood, we chose “cuttlefish” as the initial research object. In accordance with the previous transaction records of FX’s cuttlefish suppliers, we were eventually told that there were four main alternative suppliers (A1, A2, A3, and A4) after a preliminary screening. Since these alternatives have different advantages in social performance, as shown in Table 8, the optimal sustainable supplier cannot be directly chosen, and needs to determine through a comprehensive and systematic examination.

Table 8. The differentiated characteristics of the four potential suppliers.

	A1	A2	A3	A4
Feature	Newly-built	Competitive	Longer established	Second largest
Strengths	Lower price Higher delivery	Substitutable Moderate in price	Good reputation Quality assurance	Quality assurance Strategic alliance
Weaknesses	Weaker voice in the supply chain	Substitute product	Weaker delivery and response	Smaller community contributions

As most of the previous literature focused on supplier selection of manufacturing companies, but less on retail companies, we were inspired to develop a general measure for SSS and explore a feasible evaluation method. The integrated method of DEMATEL-ANP-VIKOR with hybrid information aggregation is finally proposed to help FX Supermarket select the suitable sustainable supplier from the above four alternative suppliers.

4.2. Data Collection

The data were collected within three phases. The first phase of our research investigates the interrelations of the dimension and criteria according to performance measure for sustainable suppliers from May to June 2017. In this stage, we originally issued 15 invitations to experts in the industry, 40 invitations to retail companies, and 5 to research institutions. Finally, a total of 20 experts, including 5 from industry associations, 4 from research institutes, and 11 (purchasing managers) from different retail enterprises were invited to fill the questionnaire for influence relationships of sustainable supplier evaluation criteria. The scale of pairwise comparison of the influence relationship using a score from 0–4 is shown in Appendix A. We sent a paper questionnaire and electronic questionnaire to each expert; experts had the choice of returning it by e-mail or post. Each questionnaire took about 5–10 min to compete. The data from the questionnaire were used in DEMATEL. In the second phase, after a month, we invited those 20 experts to help rate relative importance of the dimension and criteria in performance measure for sustainable supplier based on the pairwise comparison. The scale using scores from 0–9 is presented in Appendix B. Each questionnaire took about 10–15 min to compete. The data from the questionnaire were used in ANP. In the last phase, we invited 4 senior managers from the financial sector, the procurement sector, and the market sector in FX Supermarket to rate the social performance of four cuttlefish suppliers according to the history transaction record and market performance, as well as their experience and knowledge. The questionnaire for quantitative and qualitative criteria ratings is shown in Appendix C. Each questionnaire took about 10–20 min to compete. The data from the questionnaire were used in VIKOR. The entire process of data collection lasted three months, from May to July 2017.

4.3. Identifying the Relationships between Dimensions and Criteria

As described, through the data mining of a large quantity of pertinent literature, and through consultations with some executives from FX Supermarket and experts in the industry, this paper establishes an evaluation index system for SSS, as shown in Table 9 (more introduction and references can be found in Section 2.3). This measure consists of 6 primary indicators (AS1–AS6) and 24 secondary indicators (C1–C24). We adopt the hybrid raw data (precise value, interval numbers, and fuzzy numbers) to obtain information aggregation to represent the actual performance of each indicator. In Table 9, *B* is expressed as the benefit-type indicator (the bigger the better), while *C* is expressed as the cost-type indicator (the smaller the better).

Table 9. The criteria evaluation system for sustainable supplier.

Primary Criteria	Second Grade Criteria	Criteria Type	Data Type	Classification
CR (AS1)	Position in industry (c1)	Qualitative	Linguistic variable [1]	B
	Financial status (c2)	Qualitative	Linguistic variable	B
	Contractual capacity (c3)	Qualitative	Linguistic variable	B
	Strategic alliance (c4)	Qualitative	Linguistic variable	B
OM (AS2)	Business process management (c5)	Qualitative	Linguistic variable	B
	Technical support (c6)	Qualitative	Linguistic variable	B
	Quality management (c7)	Qualitative	Linguistic variable	B
	Learning & Innovation (c8)	Qualitative	Linguistic variable	B
PA(AS3)	Procurement cost (c9)	Quantitative	Interval number	C
	Product quality (c10)	Qualitative	Linguistic variable	B
	Supply flexibility (c11)	Quantitative	Precise number	B
	Product market share (c12)	Quantitative	Precise number	B
SC (AS4)	Responsiveness (c13)	Quantitative	Precise number	B
	Timely delivery (c14)	Quantitative	Precise number	B
	Customer satisfaction (c15)	Qualitative	Linguistic variable	B
	Maintenance & Compensation (c16)	Qualitative	Linguistic variable	B
GI (AS5)	Pollution production (c17)	Qualitative	Linguistic variable	C
	Pollution control (c18)	Qualitative	Linguistic variable	B
	Energy consumption (c19)	Qualitative	Linguistic variable	C
	Ecologic design (c20)	Qualitative	Linguistic variable	B
SR (AS6)	Labor relations record (c21)	Qualitative	Linguistic variable	B
	Governmental relations (c22)	Qualitative	Linguistic variable	B
	Community welfare investment (c23)	Qualitative	Linguistic variable	B
	Shareholder contract (c24)	Qualitative	Linguistic variable	B

[1] Linguistic variable will be transformed into the IVTFN in group information aggregate.

4.4. Determining the Weights Using DEMATEL-ANP

Within the measure of SSS, the target layer includes six decision aspects which are not independent of each other. For example, OM, PA, and SC clearly interact with each other, while there may be a mutual impact among CR, SR, and GI. Hence, the relationship among the elements in the target layer should be determined before solving this model.

- Step 1: Lining up a panel of 20 experts from the associations, enterprises, and researchers in the academy to judge and score the direct influence among the primary criteria applying the Delphi law, of which the indicator values were scored in accordance with the 0–4 scores. The 20 expert-scoring tables are gathered to calculate the arithmetic mean and are listed as a 7×7 direct-relation matrix A, as shown in Table 10.

Table 10. The direct-relation matrix A.

	AS1	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
AS1	0	2.95	3.15	3.25	3.05	3.25
AS2	2.8	0	2.8	3	2.2	2.25
AS3	3	2.5	0	2	2.25	2
AS4	3.1	1.95	2.2	0	1.65	2
AS5	2.25	2	2.7	2.05	0	2.3
AS6	3	2.1	2.3	2.15	2.25	0

- Step 2: Obtaining the normalized direct-relation matrix D through Equation (1), and then acquiring the comprehensive influence matrix T by Equation (2), as shown in Table 11.

Table 11. The comprehensive impact matrix T of the objective hierarchical elements.

	AS1	AS2	AS3	AS4	AS5	AS6
AS1	1.727	0.770	0.851	0.825	0.769	0.797
AS2	0.778	1.526	0.740	0.724	0.644	0.663
AS3	0.738	0.624	1.544	0.634	0.608	0.611
AS4	0.709	0.569	0.634	1.489	0.550	0.581
AS5	0.676	0.577	0.665	0.610	1.459	0.601
AS6	0.739	0.605	0.672	0.641	0.608	1.498

- Step 3: Constructing the causal map according to expert advice and repeated tests to get the threshold, which is equal to 0.55. If the value in the composite impact matrix is less than 0.55, it means that there is a clear correlation between the indicators, so the criteria with negligible relationships should be removed. Then, the influencing degree C, influenced degree R, the center degree $C + R$, and the cause degree $C - R$ are calculated, as shown in Table 12. Finally, the causal map is drawn according to $C + R$ and $C - R$, as shown in Figure 5, where the pointing arrow represents the degree of the impact exerted by other factors.

Table 12. The adjusted composite effect matrix.

	AS1	AS2	AS3	AS4	AS5	AS6	C	C+R	C-R
AS1	0.727	0.770	0.851	0.825	0.769	0.797	4.738	9.105	0.372
AS2	0.778	0.000	0.740	0.724	0.644	0.663	3.550	6.694	0.405
AS3	0.738	0.624	0.000	0.634	0.608	0.611	3.214	6.776	(0.348)
AS4	0.709	0.569	0.634	0.000	0.000	0.581	2.492	5.925	(0.942)
AS5	0.676	0.577	0.665	0.610	0.000	0.601	3.129	5.758	0.499
AS6	0.739	0.605	0.672	0.641	0.608	0.000	3.265	6.517	0.013
R	0.727	0.770	0.851	0.825	0.769	0.797	-	-	-

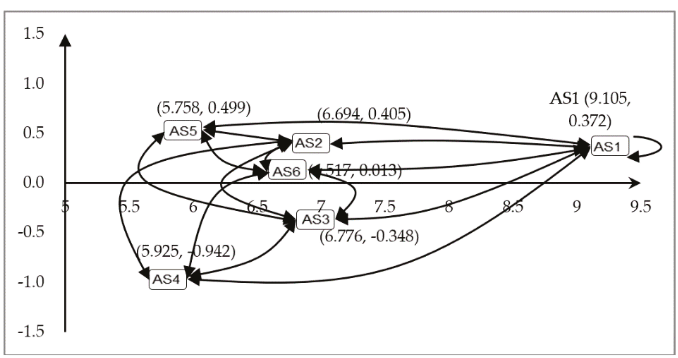

Figure 5. The cause-and-effect diagram of the primary criteria.

- Step 4: After determining the relationship between indicators through the DEMATEL, the ANP network of the sustainable suppliers' decision would be constructed, as shown in Figure 6, where the arrow pointing represents the mutual interdependence and feedback among the criteria, as shown in Appendix D.

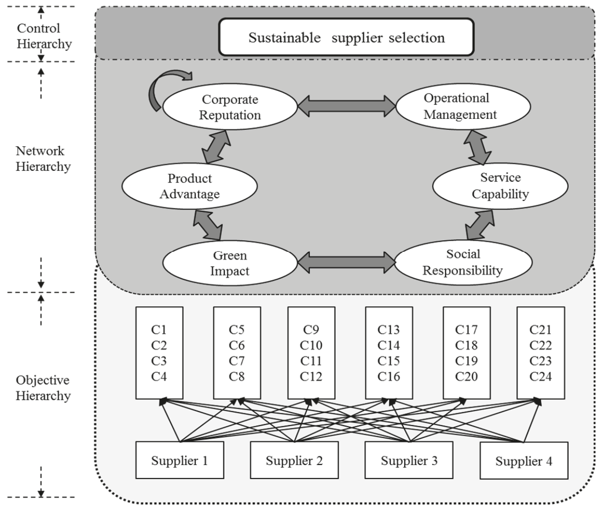

Figure 6. The map of the ANP network structure.

- Step 5: According to the causal relationship between the indicators, the judgment matrix of scale 1–9 is established, and then the unweighted super-matrix, weighted super-matrix, and limit super-matrix are obtained in succession. This paper considers the importance of the interplay of the 6 primary indicators and the 24 secondary indicators. Through the Super Decision software, the judgment matrix of the pairwise comparison in the manner of a questionnaire is inputted to compute and then perform the consistency test. Thereafter, choosing the factors to be judged in turn, the construction of the judgment matrix is repeated and its weight is determined. Finally, the unweighted super-matrix, weighted super-matrix, and limit super-matrix are established, as shown in the Appendixs E–G.
- Step 6: Achieving the weight of the indicator. On the basis of the results of the limit super-matrix, the weight of the indicators of the alternatives can be obtained, as shown in Table 13.

Table 13. The weights of the factors affecting the sustainable suppliers.

	AS1(0.112)				**AS2(0.132)**			
	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
Local weight	0.237	0.319	0.241	0.203	0.203	0.156	0.271	0.370
Global weight	0.033	0.044	0.033	0.028	0.029	0.022	0.038	0.052
	AS3(0.229)				**AS4(0.150)**			
	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}
Local weight	0.311	0.268	0.230	0.191	0.419	0.144	0.297	0.140
Global weight	0.068	0.059	0.050	0.042	0.063	0.022	0.045	0.021
	AS5(0.147)				**AS6(0.230)**			
	c_{17}	c_{18}	c_{19}	c_{20}	c_{21}	c_{22}	c_{23}	c_{24}
Local weight	0.120	0.302	0.207	0.371	0.318	0.264	0.145	0.273
Global weight	0.016	0.039	0.027	0.048	0.071	0.059	0.032	0.061

4.5. Evaluating the Social Performance of Suppliers Using VIKOR

After obtaining the weight of the primary and secondary indicators of the sustainable supplier through the DEMATEL-ANP method, this paper then carries out the numerical operation of the sustainable supplier model according to the fuzzy VIKOR method. In the data collection, the quantitative evaluation criteria are gained through the real data of the procurement and operation of FX Supermarket in 2016–2017, as shown in Table 14; the qualitative evaluation criteria are acquired by the score of the semantic value of the qualitative indicators of the four potential sustainable suppliers, as shown in Table 15.

Table 14. The quantitative evaluation values of the potential sustainable suppliers of FX.

		C9 (USD/box)	C11 (%)	C12 (%)	C13 (%)	C14 (%)
D1	**A1**	[9,13]	30	8	80	96
	A2	[11,15]	18	14	78	92
	A3	[12,16]	10	40	92	83
	A4	[13,17]	15	32	81	86
D2	**A1**	[11,15]	13	9	82	95
	A2	[13,17]	16	17	80	90
	A3	[15,19]	12	37	90	86
	A4	[14,18]	7	30	82	93
D3	**A1**	[8,12]	9	7	81	94
	A2	[10,14]	14	18	82	88
	A3	[16,20]	11	36	87	83
	A4	[10,14]	8	29	83	90
D4	**A1**	[12,16]	10	8	81	95
	A2	[10,14]	14	15	80	90
	A3	[17,21]	13	39	91	88
	A4	[11,15]	7	29	92	91

Table 15. The subjective evaluation value scored by DMs from enterprise FX.

Criteria	**D1**				**D2**				**D3**				**D4**			
	A1	**A2**	**A3**	**A4**	**A1**	**A2**	**A3**	**A4**	**A1**	**A2**	**A3**	**A4**	**A1**	**A2**	**A3**	**A4**
C1	F	MG	VG	VG	F	MG	VG	VG	F	MG	VG	VG	F	MG	VG	VG
C2	F	F	G	G	MG	P	VG	G	F	F	MG	G	MP	MG	G	G
C3	VG	MG	MG	MG	VG	F	G	MG	VG	G	F	F	VG	MG	MG	G
C4	F	G	F	G	MG	MG	MG	VG	F	VG	MP	MG	F	G	F	G
C5	P	F	MG	VG	VP	MP	F	VG	MP	MG	MG	VG	P	F	G	VG
C6	F	F	F	VG	MP	F	F	VG	MG	MG	F	VG	F	MP	F	VG
C7	P	MP	G	G	MP	P	G	VG	MP	MP	MG	MG	MP	MP	VG	G
C8	VG	MG	MP	F	VG	G	MP	MG	VG	F	P	MP	G	MG	MP	F
C10	MG	F	G	G	G	MG	VG	G	F	F	MG	G	MG	MP	G	G
C15	MG	MP	MP	G	G	MP	MP	VG	F	MP	P	MG	MG	P	MP	G
C16	VG	MG	MG	G	VG	G	F	G	VG	F	MG	G	VG	MG	G	MG
C17	VG	MG	F	G	VG	G	MG	VG	G	F	MP	G	VG	MG	F	MG
C18	MG	MG	MG	G	G	MG	F	G	G	F	MG	G	F	G	G	G
C19	MG	F	MG	F	G	MG	G	F	F	MP	F	MG	MG	F	MG	MP
C20	VP	F	G	MG	VP	MP	VG	G	VP	MG	G	F	VP	F	MG	G
C21	G	MG	G	VG	VG	F	G	VG	MG	MG	VG	VG	G	G	MG	VG
C22	MG	MP	MG	MG	G	P	G	MG	MG	MP	F	F	F	MP	F	G
C23	MG	F	MG	VP	MG	MP	G	MP	F	MG	MG	P	G	F	F	VP
C24	VG	MG	F	MG	VG	G	F	MG	VG	MG	MP	F	VG	F	MG	G

- Step 1: Normalizing the objective evaluation data. The numerical and interval data in Table 14 are normalized to eliminate the influence of the index dimension through Equations (18)–(20).
- Step 2: The semantic variables of the subjective evaluation information given by the scorers in Table 15 are transformed into the form of IVTFNs to construct the decision matrix. The evaluation

information of the subjective and objective indicators is then aggregated to obtain a comprehensive evaluation matrix, as shown in Table 16.

- Step 3: According to the weight obtained by the DEMATEL-ANP method, the weighted interval triangular fuzzy matrix is constructed. Based on the above comprehensive evaluation matrix, the VIKOR method is used to choose the optimal alternative before the PISs (A^{*2} and A^{*1}) and NIS (A^{-1}) are obtained through Equations (11)–(13).
- Step 4: The $\widetilde{S}_{ij}^{U}$ and $\widetilde{S}_{ij}^{L}$ of the potential sustainable suppliers are calculated through Equations (14)–(17), and then $\widetilde{S}_i$ and $\widetilde{R}_i$ are obtained. Further, we can acquire the cases of v by taking different parameters according to Equation (18), as shown in Table 17.
- Step 5: Ranked by $\widetilde{S}_i$, $\widetilde{R}_i$, and $\widetilde{Q}_i$; the smaller the $\widetilde{Q}_i$ value is, the better the corresponding alternative. Then, the appropriate target supplier is selected after the validity test. The priority order of the alternative sustainable suppliers is $A_4 \succ A_1 \succ A_3 \succ A_2$, given by the $\widetilde{Q}_i$ values, while the sustainable supplier A_4 has the smallest $\widetilde{Q}$ value. In order to determine whether the selected scheme satisfies Condition 1 and Condition 2 of the evaluation criteria, we can calculate $Q(A_1) - Q(A_4) = 0.372 > 1/3$, which is proved to meet the Condition 1, coupled with Condition 2 (that A_4 is also the optimal scheme ordered by $\widetilde{S}_i$ and $\widetilde{R}_i$). Furthermore, suppose the v value equates to 0, 0.5, and 1, respectively, the $\widetilde{Q}_i$ values corresponding to A_4 are still the smallest and, therefore, the supplier A_4 can be considered as the optimally sustainable supplier of the FX Supermarket based on the decision making process.

4.6. The Sensitivity Analysis

Through the sensitivity analysis, it can be determined whether the potential changes of the weights will cause deviations from the initial results [146]. This paper will adopt the perturbation method to test the sensitivity of the criteria weights to evaluate the robustness of the model. As previously defined, w_j represents the initial weight of any criterion c_j in the measures, and we let $w'_j = \gamma w_j$ after a disturbance, where $0 < w'_j < 1$. Then, the variation range of parameter γ can be expressed as $0 < \gamma < 1/w_j$. Owing to the normalization of the weight vector, the rest of the weights will also change because of the variation of w_j, and are denoted as $w'_k = \eta w_k$, $k \neq j$, $k = 1, 2, \cdots, m$, and $w'_j + \sum_{k \neq i, k=1}^{m} w'_k = 1$. This is equivalent to $\gamma w_j + \eta \sum_{k \neq i, k=1}^{m} w_k = 1$, then $\eta = (1 - \gamma w_j)/(1 - w_j)$. For each criteria weight w_j, when setting a different parameter γ, the corresponding potential supplier priority can be obtained under the VIKOR method. In the proposed model, γ is set to 4, 2, ½, and ¼, respectively, and the experiment is repeated 40 times. As shown in Figure 7, the results show that the $\widetilde{Q}_i$ value of supplier A_4 is still the smallest during 40 experiments, and supplier A_1 has 37 experiments in which it was generally consistent in second place (only in the 11th, 19th, and 26th experiments did it rank third), which means that the proposed model is relatively insensitive to the change of the criteria weights. Thus, we conclude that the robustness of the overall model is evident, and A_4 is the optimal sustainable supplier, while there is a small probability (7.5%) of it changing the order of the remaining suppliers.

Table 16. The matrix of intervals triangular fuzzy numbers of individual information aggregations.

	C1	C2	C3	C4	C5	C6
A1	[(2.5, 3.5), 5, (6.5, 7.5)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(8.5, 9.5), 10, (10.0, 10)]	[(3.0, 4.0), 5.5, (6.88, 8.0)]	[(0, 0.63), 1.25, (2.65, 3.5)]	[(2.38, 3.5), 5, (6.38, 7.5)]
A2	[(4.5, 5.5), 7, (8.0, 9.5)]	[(2.38, 3.25), 4.5, (5.88, 7)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(2.38, 3.5), 5, (6.38, 7.5)]
A3	[(8.5, 9.5), 10, (10, 10)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(4.25, 5.5), 7.0, (8, 9.13)]	[(2.5, 3.5), 5, (6.5, 7.5)]
A4	[(8.5, 9.5), 10, (10, 10)]	[(5.5, 7.5), 9, (9.0, 10.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(8.5, 9.5), 10, (10.0, 10.0)]	[(8.5, 9.5), 10, (10.0, 10)]
	C7	**C8**	**C9**	**C10**	**C11**	**C12**
A1	[(1.25, 2.5), 4, (5.5, 6.5)]	[(7.75, 9), 9.75, (9.88, 10)]	[(7.14, 7.69), 8.33, (9.09, 10.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(10, 10), 10, (10, 10)]	[(2.1, 2.1), 2.11, (2.1, 2.1)]
A2	[(0.0, 1.25), 2.5, (4, 5.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(6.67, 7.14), 7.69, (8.33, 9.09)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(6.0, 6.0), 6, (6.0, 6.0)]	[(4.2, 4.2), 4.21, (4.2, 4.2)]
A3	[(6, 7.5), 8.75, (9.25, 9.88)]	[(0.0, 1.25), 2.5, (4.0, 5.0)]	[(5.26, 5.56), 5.88, (6.25, 6.67)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(3.3, 3.3), 3.3, (3.3, 3.3)]	[(10, 10), 10, (10.0, 10.0)]
A4	[(6, 7.5), 8.75, (9.25, 9.88)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(6.25, 6.67), 7.14, (7.69, 8.33)]	[(5.5, 7.5), 9, (9.5, 10.0)]	[(5.0, 5.0), 5.0, (5.0, 5.0)]	[(7.9, 7.9), 7.89, (7.9, 7.9)]
	C13	**C14**	**C15**	**C16**	**C17**	**C18**
A1	[(9.0, 9.0), 9, (9.0, 9.0)]	[(10, 10.0), 10, (10, 10.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(8.5, 9.5), 10, (10.0, 10.0)]	[(7.75, 9), 9.75, (9.88, 10)]	[(4.5, 6.0), 7.5, (8.38, 9.25)]
A2	[(8.9, 8.9), 8.89, (8.9, 8.9)]	[(9.5, 9.5), 9.47, (9.5, 9.5)]	[(0.0, 1.25), 2, 5, (4.0, 5.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(4.25, 5.5), 7, (8.0, 9, 13)]	[(4.25, 5.5), 7, (8.0, 9.13)]
A3	[(10, 10.0), 10, (10, 10.0)]	[(8.9, 8.9), 8.95, (8.9, 8.9)]	[(0.0, 1.25), 2.5, (4.0, 5.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(4.25, 5.5), 7, (8.0, 9.13)]
A4	[(9.1, 9.1), 9.11, (9.1, 9.1)]	[(9.5, 9.5), 9.47, (9.5, 9.5)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(5.25, 7), 8.5, (9.13, 9.88)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(5.5, 7.5), 9, (9.5, 10.0)]
	C19	**C20**	**C21**	**C22**	**C23**	**C24**
A1	[(4.25, 5.5), 7, (8.0, 9.13)]	[(0.0, 0.0), 0, (1.0, 1.5)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(4, 25, 5.5), 7, (8.0, 9.13)]	[(4.25, 5.5), 7, (8.0, 9, 13)]	[(8.5, 9.5), 10, (10, 10)]
A2	[(2.38, 3.5), 5, (6.38, 7.5)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(0.0, 1.25), 2.5, (4.0, 5.0)]	[(2.38, 3.5), 5, (6.38, 7.5)]	[(4.25, 5.5), 7, (8.0, 9.13)]
A3	[(4.25, 5.5), 7, (8, 0, 9.13)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(6, 7.5), 8.75, (9.25, 9.88)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(2.38, 3.5), 5, (6.38, 7.5)]
A4	[(2.38, 3.5), 5, (6.38, 7.5)]	[(4.5, 6), 7.5, (8.38, 9.25)]	[(8.5, 9.5), 10, (10.0, 10.0)]	[(4.25, 5.5), 7, (8.0, 9.13)]	[(0, 0.5), 1, (2.25, 3.0)]	[(4.25, 5.5), 7, (8, 9.13)]

Table 17. The values of S, R, and Q for the alternative sustainable suppliers.

	$\widetilde{S}$	$\widetilde{R}$	$\widetilde{Q}$ $(v = 0)$	Ranking	$\widetilde{Q}$ $(v = 0.5)$	Ranking	$\widetilde{Q}$ $(v = 1)$	Ranking
A1	0.499	0.057	0.306	2	0.372	2	0.437	2
A2	0.728	0.071	1.000	4	1.000	4	1.000	4
A3	0.518	0.070	0.962	3	0.723	3	0.484	3
A4	0.321	0.050	0.000	1	0.000	1	0.000	1

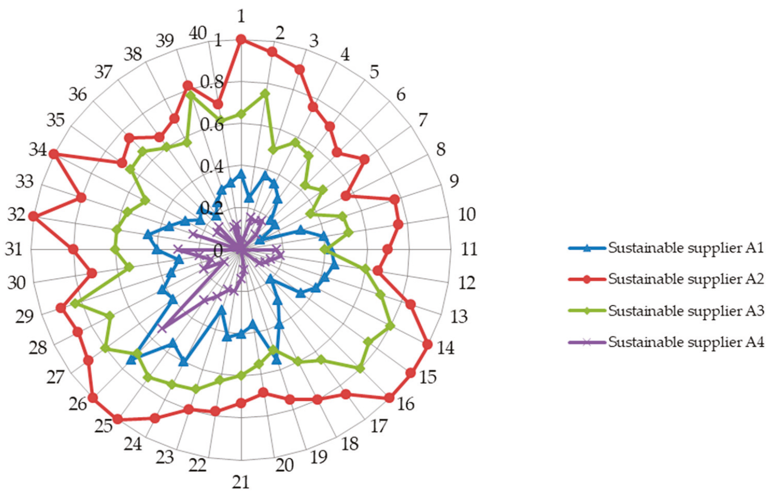

Figure 7. The sensitivity analysis under the VIKOR method.

4.7. Comparative Study

We also use the TOPSIS method to make the decision of the normalized decision matrix in the case analysis and to make a comparison of the results under these two integrated methods (DEMATEL-ANP-TOPSIS and DEMATEL-ANP-VIKOR). Ordered by the consolidation function $\varepsilon_i = D_i^- / (D_i^- + D_i^+)$ for the alternatives, where D_i^+ represents the weighted distance from supplier A_i to the PIS and D_i^- represents the weighted distance from supplier A_i to the NIS; based on the PIS (f^*) and the NIS (f^-) calculated by the previous decision matrix, the weighted relative closeness coefficient of the four potential suppliers to PIS can be obtained as:

$$(\varepsilon_1^+, \varepsilon_2^+, \varepsilon_3^+, \varepsilon_4^+) = (0.691, 0.596, 0.685, 0.756)$$

Then we can get the priority, which is $A_4 \succ A_1 \succ A_3 \succ A_2$. Thus, the optimally sustainable supplier is A_4, the same as the result obtained by the VIKOR method. This paper has discussed the superiority of the VIKOR method to the TOPSIS method in the above chapters. Here we will verify the drawbacks of the TOPSIS method from the perspective of the simulation data. The sensitivity analysis is conducted to check the decision results obtained from TOPSIS. Similarly, for each criteria weight w_j, when taking different γ values, using the TOPSIS method can get the corresponding potential supplier priority. In the proposed hybrid TOSIS algorithm, the weights of the 24 criteria are perturbed while assigning γ to be 4, 2, ½, and ¼, respectively, and repeating the experiment 40 times.

As shown in Figure 8, the $\widetilde{Q}_i$ value of supplier A_4 is also the smallest during the 40 experiments, but the orders involved with other suppliers changed a lot. The supplier A_1 has 6 occurrences of order changes in the 40 experiments, which means that the percentage of instability comes to 15%. It can be seen that the TOPSIS decision method is relatively sensitive to the change of the weights of the evaluation value compared with the VIKOR method (the VIKOR method is 7.5% and the TOPSIS method is 15%).

In conclusion, the DEMATEL-ANP-VIKOR method shows more advantages than the DEMATEL-ANP-TOPSIS method in terms of theoretical analysis, numerical experiment, and the sensitivity analysis. In this paper, the model of DEMATEL-ANP-VIKOR is more robust to deal with the hybrid data with incomparable information under an uncertain environment than the traditional TOPSIS method, and this result basically confirms and supports the argument of Opricovic and Tzeng [24].

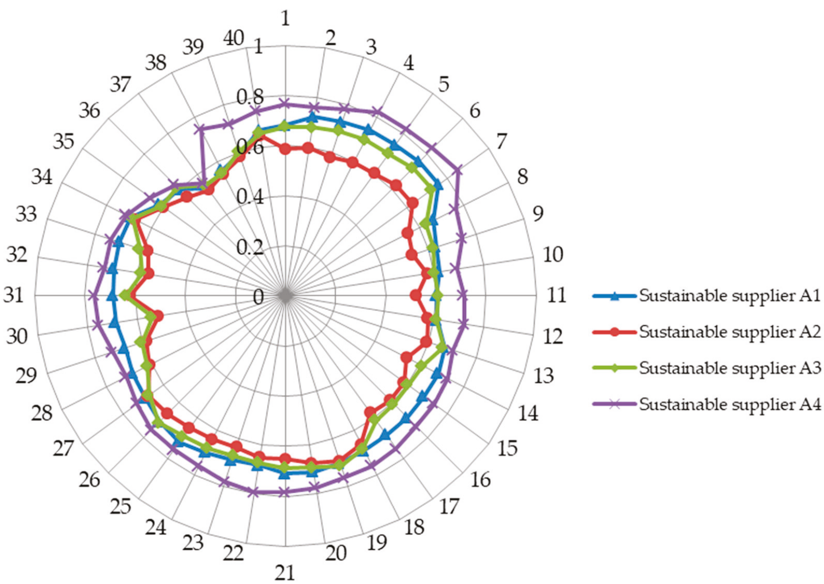

Figure 8. The sensitivity analysis under the TOPSIS method.

5. Implications and Discussions

Despite the increasing amount of literature on sustainable suppliers in recent years, there is still little research on supplier sustainability in retail enterprises. Correspondingly, the measure to evaluate and choose sustainable suppliers is imperfect and needs improving. This paper attempts to contribute a theoretical supplement. After extensive literature reviews and consultations with some experts in the industry, based on the TBL theory and stakeholder theory, a measure including economic, green (environmental), and social dimensions has been proposed. Among them, we introduce 4 primary criteria covering CR, OM, PA, and SC to assess economic performance, and use Pollution production, Pollution control, and Energy consumption and Ecologic design to characterize GI. Most importantly, we require suppliers to provide evidence of their social responsibility fulfillment to internal and external stakeholders. Among the 6 primary criteria, SR obtains the greatest weight (0.230), and PA (0.229) is scored in second place with a very small gap, followed by SC, GI, OM, and CR. This weight ranking is intuitively devised, as we used to think that economic performance should be the most important, even among sustainable suppliers. Most experts in the case believe that the sustainability of suppliers should first be reflected in their corporate ethics, which is consistent with Zimmer, Froehling and Schultmann [7]. In spite of this, sub-criteria including cost, quality, delivery, and responsiveness are generally perceived to be foremost priorities in the traditional selection of suppliers [149], which are also important indicators when the retail company judges its suppliers. It is important to mention that

Labor relations records, as transparent and measurable indicators of social responsibility, are regarded as the most important factors within the 24 s grade criteria. This evidence is consistent with the study of Amindoust, Ahmed, Saghafinia and Bahreininejad [4]. Moreover, the new indicators we proposed, such as Position in industry (0.033), Strategic alliance (0.028), Business process management (0.029), Learning (0.052), Customer satisfaction (0.045), Governmental relations (0.059), and Shareholder contract (0.061) have been given high weights, which also confirm the applicability and relative importance in SSS of retail enterprises. Nevertheless, in order to be more applicable and robust, the measures we have proposed for SSS cannot be static, and need to be dynamic adjusted, increased or reduced, according to the changes in the real environment and demand of retail enterprises.

Along with the logic of the DEMATEL-ANP-VIKOR method, we have improved the process of weight determination under DEMATEL-ANP, which reduces the amount of calculation required to get the same result. This evidence was reinforced through discussion with experts from the case company, in which they indicated that the DEMATEL-ANP was easy to implement in determining the weighting and causal relationships between multiple performance criteria [28]. The VIKOR method is applied to select suitable sustainable suppliers and to analyze gaps in the desired level of sustainable performance for each supplier. By conducting 40 sensitivity experiments, A4 was never changed as the best sustainable supplier in the case, while the other sort deviated only 3 times, which shows the robustness of the proposed method. To further verify the applicability of this method, we introduce another typical compromise method, TOPSIS, to find a sustainable alternative based on the same case. We obtained the same solution by TOPSIS, although the robustness of TOPSIS was weaker than the proposed method, as multiple deviations of the prioritizations produced by TOPSIS occurred in our sensitivity analysis. In contrast, the VIKOR algorithm showed robustness when the indicator weights shifted, which helped the DMs to provide decision-making references to a certain extent. This result provides realistic evidence for the comparative analysis of Opricovic and Tzeng [24].

Interestingly, the executives of FX Supermarket were particularly surprised when we told them about the results of sustainable suppliers, because in their view, A3 is the leading company in the market, and intuitively, it should be the most sustainable. The fact that A4 is more suitable than A3 is largely because the former performed better in terms of social criteria, while there was no big difference in the characteristics and distribution of the products they provide. We find it difficult to judge social responsibility based on solely experience and knowledge of scorers, instead of by a comprehensive measure. As for most companies, they are often more sensitive to economic performance than the social impact of suppliers. Our results inspire a deeper understanding of sustainable suppliers and sustainable procurement, and help managers devise strategies for effectively minimizing gaps in the sustainable performance of potential suppliers.

The introduction and use of the hybrid information aggregation is one of the main contributions in this paper, which can address the duality (qualitative and quantitative, precise and fuzzy) of semantic evaluation under a more realistic environment. This mechanism was recognized through discussion with the four managers from FX Supermarket, in which they thought the use of mixed information values could better characterize the scorer's judgment. We propose three types of criteria value, namely: precise number, interval number and fuzzy number. Quantitative indicators are characterized by precise number and interval number, while qualitative indicators are scored by IVTFNs. The use of IVTFNs makes it easier and faster for experts to make judgments and avoid mistakes caused by hesitation and non-intuition. Through the integration of hybrid information aggregation and DEMATEL-ANP-VIKOR, qualitative and quantitative indicators characterized by different data type can be measured and compared in the same dimension, which increases the systematic and comprehensive evaluation of sustainable supplier.

This paper focuses on the SSS of retail enterprises, because these enterprises have begun to place much attention on the sustainability of their product sources in recent years. For example, Swiss retail giant Migros decided to sell 100% sustainable resources seafood before 2020; Wal-Mart introduced a Supplier Scorecard on Sustainability, and has constantly increased its applicable categories since

2012. Considering that there are few sustainable performance measures and methods that have been widely accepted, this paper tries to promote an evaluation framework and model for the retail industry based on the FX case. The retail industry in emerging markets shows different features from that of developed countries, and has a slower pace of development, which means that the SSCM and sustainable procurement have not received widespread attention. However, nobody can ignore its importance; as we introduced in section one, due to the lack of supervision and proper selection of suppliers in emerging economies, Apple almost ruined their brand, even though they have taken many social initiatives within the company. For retail enterprises in emerging economies, global sustainable procurement has begun to be deployed, and the Chinese government has also called for more retail companies to participate in sustainable supplier programs. In the future, sustainable supplier management of retail companies in emerging markets will become indispensable for core firms to strengthen the sustainability of their supply chain.

6. Conclusions and Future Research

To facilitate a sustainable supply chain in the retail industry, a TBL-based conceptual measure for SSS was presented. By identifying the economic benefits, green impact, and social performance of alternative suppliers, a hybrid MCDM based on hybrid information aggregation was applied to a sample retail enterprise.

Little attention has been paid to SSS in retail industry, and there is almost no systemic and standard measure that could be used to assess the sustainability of suppliers. Based on this gap, through an extensive literature review and by consultations with experts in the industry, this paper proposes a sustainable performance measure in accordance with the principle of the TBL. In addition to the reservation of some traditional highly-cited criteria, new indicators such as strategic alliance, learning, governmental relations, and shareholder contracts have been presented and proved to be applicable to the evaluation framework. This paper also contributes to the measurement of supplier social responsibility by following the logic of the stakeholder theory. The measure has been approved by practitioners in retail enterprises who are committed to sustainable procurement, such as FX Supermarket and Wal-Mart.

On the other hand, considering the limitations of the supplier evaluation methods in previous studies, this paper proposes an improved DEMATEL-ANP-VIKOR method to seek sustainable suppliers. Based on the requirements of scorers in reality, we introduce the data types of precise number and interval number to characterize quantitative indicators and IVTFN to represent subjective judgment, which can further be integrated into a set of mixed information and become a hybrid input for DEMATEL-ANP-VIKOR method. This model was validated in the case of FX Supermarket, when we help them find the optimal sustainable supplier of "cuttlefish" based on the proposed measure and method, according to the market performance and operating conditions of four potential suppliers. Through the sensitivity analysis and comparison with TOPSIS, the proposed method shows more robustness, and embodies its superiority in selecting appropriate suppliers, as it considers both maximum group utility and individual regret to measure the gaps between alterative and ideal solutions, which can strengthen the ability to conduct social performance assessments of suppliers.

As more and more retail enterprises have joined the campaign of sustainable procurement, especially in the emerging market, the means to screen and manage sustainable suppliers will be an urgent question. Of course, there are many industries that also need to consider the choice of sustainable suppliers, such as construction. This paper provides a certain theoretical supplement for the discipline of sustainability and supplier selection. Also, the sustainable performance measure and integrated method can play an audit role for practitioners to evaluate the performance of the SSCM practices of relative suppliers.

Considering that the SSS is a complex engineering problem, there is still room for improvement. This paper proposed a social performance measure for supplier selection based on a retail enterprise, but it didn't consider some intangible factors such as supply chain relationship and binding trade secrets, which may affect the scorer's judgment to some degree. More indicators from various dimensions should be considered and chosen according to real-world applications. Considering that suppliers may change their sustainability due to the pressure of core enterprises, in order to select the suitable suppliers dynamically, evaluating the alternatives using the MCDM method at each stage can solve this issue, but it may require much time and financial investment. A dynamic monitoring and evaluation approach to quickly select suppliers could be applied in future research. The priority order of the sustainable suppliers using the integrated MCDM method with hybrid information aggregation in this study were only scored and determined by four related department managers. Also, the alternatives are limited to four suppliers. Increasing the number of scorers, especially those from the same industry and alternative suppliers, may allow us to better compare scenarios and validate the proposed models and methods.

Author Contributions: Z.X. and X.Z. designed the whole study, proposed the conceptualization and did the investigation; X.Z. conducted data collection, modeling, and results analysis and wrote the original draft; Z.X. was responsible for funding acquisition, project administration and supervision and also reviewed and edited the paper. All authors read the final manuscript and approved it for final submission.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Questionnaire for Influence Relationships of SSS Criteria
Dear Sir/Madam,

We are currently undertaking a questionnaire survey for influence relationships of each criterion in the hierarch criteria system.

This survey is an important part of the research on the sustainable supplier evaluation and has a direct impact to the final solution. The main purpose is to understand the mutual influence of the indicators in the sustainable supplier evaluation system, in order to remove factors that affect the follow-up weight judgment.

A questionnaire that requires you to assign the mutual influences for criteria is attached in the e-mail. We hope you could look over the questionnaire and thoughtfully make the decision under your practical experience and knowledge. The questionnaire should take you about 5–10 min to compete.

All answers are confidential and all identifying information will be kept anonymous. And there is not any right or wrong answer in the options setting, please make the judgment according to your own experience and real understanding.

Thanks for your support and help.

PART ONE: The Basic Information of The Evaluator

Please fill in the appropriate options in the space.
1. The following identity description is suitable for you _____.
A. Government B. Academy C. Industry

PART TWO: Evaluation of Mutual Influence of Indicators

1. Measurement scale for pair-wise comparisons

In this questionnaire, the degree of interaction between the criteria in the sustainable supplier evaluation system is scored from 0–4. The meaning of each score is shown below:

Score	0	1	2	3	4
Impact	No Impact	Lower Impact	Moderate Impact	Higher Impact	Very higher Impact

2. Illustrated example

The following table shows that: (1) AS1 has no impact on AS2, so AS1/AS2 = 0; (2) AS2 has lower impact on AS3, so AS2/AS3 = 1; (3) AS3 has moderate impact on AS4, so AS3/AS4 = 2; (4) AS4 has higher impact on AS5, so AS4/AS5 = 3; (5) AS5 has very higher impact on AS6, so AS5/AS6 = 4.

	AS1	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
AS1	0	0				
AS2		0	1			
AS3			0	2		
AS4				0	3	
AS5					0	4
AS6						0

Please rate the correlation between indicators according to your experience and understanding below (see the indicator from the measures proposed in Section 2.3. We provide a detailed explanation of the index, which is omitted here for shortening the length of this paper, similarly hereinafter).

	AS1	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
AS1	0					
AS2		0				
AS3			0			
AS4				0		
AS5					0	
AS6						0

This is the end of the questionnaire, thanks again for your participation and support!

Appendix B

Questionnaire for Assigning the Importance of SSS Criteria
Dear Sir/Madam,

We are currently undertaking a questionnaire survey for assigning the relative importance of each criterion in the hierarch index system. The weights assignment plays a significant role in our study and has a direct impact to the final results. We are very glad to invite you to participate in this research project.

A questionnaire that requires you to assign the relative importance for criteria is attached in the e-mail. We hope you could look over the questionnaire and thoughtfully make the decision under your practical experience and knowledge. The questionnaire should take you about 10–15 min to compete and you may be required to make the comparison again if inconsistency happens in the evaluation process.

We guarantee that your responses will only be used and accessed by researchers in order to keep confidential and private. We promise not to share your names, address and other personal/organization details. And there is not any right or wrong answer in the options setting, please make the judgment according to your own experience and real understanding. If you have any further assistance or questions about completing the questionnaire and our research, please contact us through the e-mail.

Thank you for your support and help.

1. Measurement scale for pair-wise comparisons

The questionnaire uses the 9-point scale to assess the importance of the evaluation index of the sustainable suppliers. The meanings of the scores are shown in the table below:

Table A1. 1–9 scale of ANP

Importance	Numerical Judgments
Elements *i* and *j* are equally important.	1
Element *i* is equally to more important than *j*.	2
Element *i* is more important than *j*.	3
Element *i* is equally to moderately more important than *j*.	4
Element *i* is moderately more important than *j*.	5
Element *i* is equally to strongly more important than *j*.	6
Element *i* is strongly more important than *j*.	7
Element *i* is equally to extremely more important than *j*.	8
Element *i* is extremely more important than *j*.	9
Source: Saaty (2000)	

2. Illustrated example

The following table shows that: (1) Both A and B are equally preferred, so A/B = 1; (2) B is moderately preferred to C, so B/C = 3; (3) D is strongly preferred to C, so D/C = 5 and C/D is therefore 1/5.

	A	B	C	D
A	1	1		
B		1	3	
C			1	1/5
D				1

Please rate the relative importance between indicators according to your experience and understanding below.

First class criteria

	AS1	AS2	AS3	AS4	AS5	AS6
AS1	1					
AS2		1				
AS3			1			
AS4				1		
AS5					1	
AS6						1

Second class criteria

Corporate reputation (AS1)—Pair-wise comparison of sub-criteria under AS1

AS1	C1	C2	C3	C4
C1	1			
C2		1		
C3			1	
C4				1

Operations management (AS2)—Pair-wise comparison of sub-criteria under AS2

AS2	C5	C6	C7	C8
C5	1			
C6		1		
C7			1	
C8				1

Product Advantage (AS3)—Pair-wise comparison of sub-criteria under AS3

AS3	C9	C10	C11	C12
C9	1			
C10		1		
C11			1	
C12				1

Service capability (AS4)—Pair-wise comparison of sub-criteria under AS4

AS4	C13	C14	C15	C16
C13	1			
C14		1		
C15			1	
C16				1

Green impact (AS5)—Pair-wise comparison of sub-criteria under AS5

AS5	C17	C18	C19	C20
C17	1			
C18		1		
C19			1	
C20				1

Social responsibility (AS6)—Pair-wise comparison of sub-criteria under AS6

AS6	C21	C22	C23	C24
C21	1			
C22		1		
C23			1	
C24				1

This is the end of the questionnaire, thanks again for your participation and support!

Appendix C Questionnaire for Quantitative and Qualitative Criteria Ratings

Dear Sir/Madam,

We are currently undertaking a questionnaire survey of quantitative and qualitative criteria ratings for sustainable supplier selection.

The quantitative and qualitative criteria scorings play a significant role in our study and have a direct impact to the final results. We are very glad to invite you to participate in this research project. The main purpose of the scoring table is to understand the status quo of four potential suppliers of FX Supermarket from partial qualitative indicators and to make scientific competitiveness to each firm on the basis of the combination of statistical data related to quantitative indicators evaluation.

A questionnaire that requires you to rate the evaluation indicators of the target company is attached in the e-mail. We hope you could look over the questionnaire and thoughtfully make the decision under your practical experience and knowledge. The questionnaire should take you about 10–20 min to compete.

All answers are confidential and all identifying information will be kept anonymous. And there is not any right or wrong answer in the options setting, please make the judgment according to your own experience and real understanding.

Thanks for your support and help.

PART ONE The Basic Information of The Evaluator

Please fill in the appropriate options in the space.
1. Your department is _____.
A. Finance B. Purchasing C. Product D. Marketing

PART TWO Quantitative Indicator Score

Please rate the following quantitative indicators based on historical business information and your experience and knowledge.

☐ Procurement cost (C9)

For each box of product Y, please give the **interval value** of the procurement price listed by every supplier.

(Unit: USD)

	(USD/Box)
Supplier 1	[______, ______]
Supplier 2	[______, ______]
Supplier 3	[______, ______]
Supplier 4	[______, ______]

Give the **precise percentage** of the following four indicators for every supplier.

☐ Supply flexibility (C11)

	(%)
Supplier 1	
Supplier 2	
Supplier 3	
Supplier 4	

☐ Product market share (C12)

	(%)
Supplier 1	
Supplier 2	
Supplier 3	
Supplier 4	

☐ Responsiveness (C13)

	(%)
Supplier 1	
Supplier 2	
Supplier 3	
Supplier 4	

☐ Timely delivery (C14)

	(%)
Supplier 1	
Supplier 2	
Supplier 3	
Supplier 4	

PART THREE Qualitative Indicator Score

In the mark sheet, the 7-level language variables are used to rate the indicators of the sustainable suppliers. The meanings of the semantic variables are as follows:

Language Variables	VP	P	MP	F	MG	G	VG
Meaning	Very poor	Poor	Moderate poor	Fair	Moderately good	good	Very good

Please indicate with an X in the box which is appropriate for each sustainable supplier's performance.

☐ Position in industry (C1)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Financial status (C2)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Contractual capacity (C3)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Strategic alliance (C4)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Business process management (C5)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Technical support (C6)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Quality management (C7)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Learning & Innovation (C8)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Product quality (C10)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Customer satisfaction (C15)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Maintenance & Compensation (C16)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Pollution production (C17)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Pollution control (C18)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Energy consumption (C19)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Ecologic design (C20)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Labor relations record (C21)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Governmental relations (C22)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Community welfare investment (C23)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

☐ Shareholder contract (C24)

	VP	P	MP	F	MG	G	VG
Supplier 1							
Supplier 2							
Supplier 3							
Supplier 4							

This is the end of the questionnaire, thanks again for your participation and support!

Appendix D

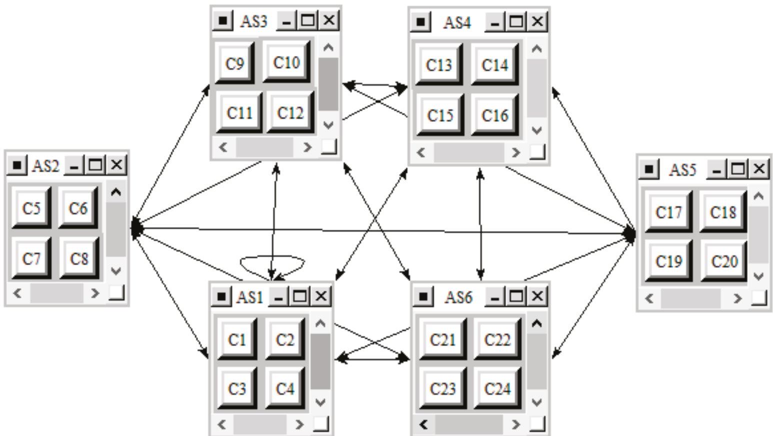

Figure A1. Implementation of Network Structure of the SSS.

Appendix E

Table A2. ANP Unweighted Supermatrix for the SSS Decision Network.

		AS1				AS2				AS3				AS4				AS5				AS6			
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**	**C21**	**C22**	**C23**	**C24**
AS1	**C1**	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237
	C2	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319	0.319
	C3	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241
	C4	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203
AS2	**C5**	0.203	0.203	0.203	0.203	0.000	0.000	0.000	0.000	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203
	C6	0.156	0.156	0.156	0.156	0.000	0.000	0.000	0.000	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156
	C7	0.271	0.271	0.271	0.271	0.000	0.000	0.000	0.000	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271
	C8	0.370	0.370	0.370	0.370	0.000	0.000	0.000	0.000	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370	0.370
AS3	**C9**	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.000	0.000	0.000	0.000	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311
	C10	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.000	0.000	0.000	0.000	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268
	C11	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.000	0.000	0.000	0.000	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230
	C12	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.000	0.000	0.000	0.000	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191	0.191
AS4	**C13**	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.000	0.000	0.000	0.000	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.419
	C14	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.000	0.000	0.000	0.000	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144
	C15	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.000	0.000	0.000	0.000	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297
	C16	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.000	0.000	0.000	0.000	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140
AS5	**C17**	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.120	0.120	0.120	0.120
	C18	0.302	0.302	0.299	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.302	0.302	0.302	0.302
	C19	0.207	0.207	0.210	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.207	0.207	0.207	0.207
	C20	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.371	0.371	0.371	0.371
AS6	**C21**	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.000	0.000	0.000	0.000
	C22	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.264	0.000	0.000	0.000	0.000
	C23	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.000	0.000	0.000	0.000
	C24	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.273	0.000	0.000	0.000	0.000

Appendix F

Table A3. ANP Weighted Supermatrix for the SSS Decision Network.

		AS1				AS2				AS3				AS4				AS5				AS6			
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**	**C21**	**C22**	**C23**	**C24**
AS1	**C1**	0.027	0.027	0.027	0.027	0.032	0.032	0.032	0.032	0.034	0.034	0.034	0.034	0.031	0.031	0.031	0.031	0.032	0.032	0.032	0.032	0.037	0.037	0.037	0.037
	C2	0.036	0.036	0.036	0.036	0.043	0.043	0.043	0.043	0.045	0.045	0.045	0.045	0.042	0.042	0.042	0.042	0.044	0.044	0.044	0.044	0.051	0.051	0.051	0.051
	C3	0.027	0.027	0.027	0.027	0.032	0.032	0.032	0.032	0.034	0.034	0.034	0.034	0.032	0.032	0.032	0.032	0.033	0.033	0.033	0.033	0.038	0.038	0.038	0.038
	C4	0.023	0.023	0.023	0.023	0.027	0.027	0.027	0.027	0.029	0.029	0.029	0.029	0.027	0.027	0.027	0.027	0.028	0.028	0.028	0.028	0.032	0.032	0.032	0.032
AS2	**C5**	0.027	0.027	0.027	0.027	0.000	0.000	0.000	0.000	0.034	0.034	0.034	0.034	0.038	0.038	0.038	0.038	0.028	0.028	0.028	0.028	0.037	0.037	0.037	0.037
	C6	0.021	0.021	0.021	0.021	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026	0.030	0.030	0.030	0.030	0.021	0.021	0.021	0.021	0.028	0.028	0.028	0.028
	C7	0.036	0.036	0.036	0.036	0.000	0.000	0.000	0.000	0.045	0.045	0.045	0.045	0.051	0.051	0.051	0.051	0.037	0.037	0.037	0.037	0.049	0.049	0.049	0.049
	C8	0.049	0.049	0.049	0.049	0.000	0.000	0.000	0.000	0.061	0.061	0.061	0.061	0.070	0.070	0.070	0.070	0.050	0.050	0.050	0.050	0.067	0.067	0.067	0.067
AS3	**C9**	0.071	0.071	0.071	0.071	0.087	0.087	0.087	0.087	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110	0.084	0.084	0.084	0.084	0.082	0.082	0.082	0.082
	C10	0.061	0.061	0.061	0.061	0.075	0.075	0.075	0.075	0.000	0.000	0.000	0.000	0.095	0.095	0.095	0.095	0.073	0.073	0.073	0.073	0.071	0.071	0.071	0.071
	C11	0.053	0.053	0.053	0.053	0.065	0.065	0.065	0.065	0.000	0.000	0.000	0.000	0.082	0.082	0.082	0.082	0.063	0.063	0.063	0.063	0.061	0.061	0.061	0.061
	C12	0.044	0.044	0.044	0.044	0.054	0.054	0.054	0.054	0.000	0.000	0.000	0.000	0.068	0.068	0.068	0.068	0.052	0.052	0.052	0.052	0.050	0.050	0.050	0.050
AS4	**C13**	0.063	0.063	0.063	0.063	0.058	0.058	0.058	0.058	0.078	0.078	0.078	0.078	0.000	0.000	0.000	0.000	0.076	0.076	0.076	0.076	0.086	0.086	0.086	0.086
	C14	0.022	0.022	0.022	0.022	0.020	0.020	0.020	0.020	0.027	0.027	0.027	0.027	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026	0.030	0.030	0.030	0.030
	C15	0.045	0.045	0.045	0.045	0.041	0.041	0.041	0.041	0.055	0.055	0.055	0.055	0.000	0.000	0.000	0.000	0.054	0.054	0.054	0.054	0.061	0.061	0.061	0.061
	C16	0.021	0.021	0.021	0.021	0.019	0.019	0.019	0.019	0.026	0.026	0.026	0.026	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026	0.029	0.029	0.029	0.029
AS5	**C17**	0.018	0.018	0.018	0.018	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.023	0.023	0.023
	C18	0.044	0.044	0.044	0.044	0.056	0.056	0.056	0.056	0.057	0.057	0.057	0.057	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.059	0.059	0.059
	C19	0.030	0.030	0.031	0.030	0.038	0.038	0.038	0.038	0.039	0.039	0.039	0.039	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040
	C20	0.054	0.054	0.054	0.054	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072	0.072	0.072	0.072
AS6	**C21**	0.073	0.073	0.073	0.073	0.083	0.083	0.083	0.083	0.101	0.101	0.101	0.101	0.103	0.103	0.103	0.103	0.087	0.087	0.087	0.087	0.000	0.000	0.000	0.000
	C22	0.061	0.061	0.061	0.061	0.069	0.069	0.069	0.069	0.084	0.084	0.084	0.084	0.085	0.085	0.085	0.085	0.072	0.072	0.072	0.072	0.000	0.000	0.000	0.000
	C23	0.033	0.033	0.033	0.033	0.038	0.038	0.038	0.038	0.046	0.046	0.046	0.046	0.047	0.047	0.047	0.047	0.040	0.040	0.040	0.040	0.000	0.000	0.000	0.000
	C24	0.063	0.063	0.063	0.063	0.072	0.072	0.072	0.072	0.087	0.087	0.087	0.087	0.088	0.088	0.088	0.088	0.075	0.075	0.075	0.075	0.000	0.000	0.000	0.000

Appendix G

Table A4. ANP Limit Supermatrix for the SSS Decision Network.

		AS1				AS2				AS3				AS4				AS5				AS6			
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
AS1	C1	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
	C2	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
	C3	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
	C4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
AS2	C5	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
	C6	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
	C7	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
	C8	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
AS3	C9	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068
	C10	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
	C11	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
	C12	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
AS4	C13	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
	C14	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
	C15	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
	C16	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
AS5	C17	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
	C18	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
	C19	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
	C20	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048
AS6	C21	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
	C22	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
	C23	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
	C24	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061

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A Game Theoretic Approach for Improving Environmental and Economic Performance in a Dual-Channel Green Supply Chain

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Abstract: In this paper, we investigate economic performance and environmental performance of a dual-channel green supply chain (GSC). Given that most relevant literature still focus on the descriptive aspect of GSC, we adopt game theoretic approach rather than qualitative analysis method to address the following problems: (1) How can the integration of environmental and economic sustainability goals be achieved in GSC? (2) What is the impact of customer environmental awareness on the green level and profitability of the GSC? (3) How does the market demand changes in the presence of the online direct channel in addition to the traditional one? We establish four game models, which are decentralized scenario, centralized scenario, retailer-led revenue-sharing scenario and bargaining revenue-sharing scenario. In the decentralized scenario, participants in a GSC make individual decisions based on their specific interests. In the centralized scenario, the GSC is regarded as a whole and the participants make collective decisions to maximize the overall profit of the GSC. In addition, in the two revenue-sharing scenarios, revenue-sharing contracts as the important profit coordination systems are set up and the revenue-sharing ratio is determined either by the retailer or through bargaining. Moreover, the cost of green product research and development, customer environmental awareness and price sensitivity are also taken into account in the four scenarios. By comparing and analyzing the four game models, we recommend the two revenue-sharing scenarios as the optimum choice and improving green awareness as a feasible strategy to achieve the integration of economic and environmental goals of the GSC. Additionally, we find that online sales has become a major distribution channel of the GSC.

Keywords: sustainability; green supply chain; green degree; game model

1. Introduction

Human activities have to a large extent changed the functioning of the planetary systems [1]. In order to curb the ecological deterioration, sustainable development strategy should be implemented [2]. With regard to corporate sustainability, the lens is beginning to be widened from a specific company to the entire supply chain (SC) [3]. In addition, the impact on environment as well as resource use efficiency need to be considered at the level of supply chain management (SCM) rather than within the boundary of a company [4]. Consequently, the concept of green supply chain (GSC) was proposed and has gained rapidly growing attention from both academia and industry [5].

In contrast to traditional SCM, which typically focuses on economic performance, green supply chain management (GSCM) aims at the integration of environmental and economic sustainability [6]. However, there is still conflicting viewpoints on whether such integrated goals could be achieved [7]. Some researchers claim that the environmental improvement does not always lead to profitability and sometimes may conflict with the economic goal [8]. On the other hand, some researchers argue that GSCM practices may improve a company's economic performance [9]. These indicate that advancing the green level of the GSC has both negative and positive impacts on economic performance [10]. Nevertheless, turning a blind eye to environmental issues is no longer an option for a company, and GSCM is thus an indispensable requirement [11].

Moreover, customer purchasing behavior has become an important factor affecting the GSCM implementation with the tremendous increase of global consumption [12]. Many investigations indicate that more customers than ever have shown their environmental concerns and desires to purchase green products [13]. However, there is a gap between consumers' positive attitudes and actual actions, and green consciousness does not always lead to green purchasing behavior [14]. In addition, rapid development of the Internet has significantly changed customer purchasing behavior and the structure of GSC distribution [15]. The rise of online shopping prompts manufacturers to adopt dual-channel strategy, which may expand market share, reduce costs and increase profits [16].

Motivated by everything mentioned above, we investigate the alignment issues between environmental and economic performance of GSC. Previous research mainly focused on description, case study, survey and other empirical methods. In this paper, we adopt game theoretic approach rather than qualitative analysis to answer the following questions:

(1) How can the integration of environmental and economic sustainability goals be achieved in GSCM?
(2) What is the impact of customer environmental awareness on the green level and the profitability of the GSC?
(3) How does the market demand change in the presence of the online direct channel in addition to the traditional one?

In the process of problem-solving, we establish four game models based on a dual-distribution GSC: (i) decentralized scenario where the manufacturer and the retailer of the GSC make decisions independently based on their own interests; (ii) centralized scenario where the GSC is treated as a whole and the manufacturer and the retailer make collective decisions to maximize the overall profit of the GSC; (iii) retailer-led revenue-sharing scenario where the profit coordination mechanisms are set up and the retailer determines the revenue-sharing ratio; (iv) bargaining revenue-sharing scenario where the manufacturer and the retailer determine the revenue-sharing ratio through bargaining in the profit coordination mechanisms. Moreover, the cost of green product research and development (R&D), customer environmental awareness and price sensitivity are also taken into account in the four scenarios.

The main contributions of this paper are presented as follows. First, a game theoretic approach is adopted, and the equilibrium solutions are calculated in four different scenarios. Second, environmental and economic performances in the four scenarios are compared and analyzed to help make decisions in GSCM practice. Third, we assume that the manufacturer can sell green products to customers through both the online direct channel and the traditional channel. Finally, factors such as green product R&D cost, customer green sensitivity and price sensitivity, which affect the green level and profitability of GSCM, are taken into account.

The rest of the paper is organized into six sections. In Section 2, a brief review of relevant literature is provided. In Section 3, the problem structure is described and four game models are introduced. In Section 4, the optimal solutions of the four scenarios are acquired. In Section 5, the four game models are compared and analyzed. Section 6 provides a numerical example to illustrate the sensitivity of the optimal solutions to some parameters. Finally, conclusions and future research directions are outlined in Section 7.

2. Literature Review

SC is a vertical sequence of independent transactions, which can be viewed as a flow of material, products and information and a set of corporate activities [17]. It is not surprising that corporate sustainable strategies have been extended through the SC for the broader adoption and development of sustainability [3]. GSCM is an effective management tool and philosophy to embed environmental sustainability into SCM [18]. In addition, many activities are involved in GSCM, such as green product design, materials acquisition, green manufacturing processes, distribution, use, and resource recycling [19]. However, the scope of GSCM in the literature has varied according to the goal of the investigator [20]. In this paper, we shall focus on the manufacturer-retailer-customer relationship and pertinent activities of green production, green marketing and green purchasing in the dual-channel structure.

Environmental and economic performances of GSM have been a topic of intense interest in GSCM literature, where both positive and negative relations between the two performances are observed. As for research methods, survey research and case study are dominant and thus most relevant literature still concentrate on the qualitative aspect of GSCM [21]. In addition, many of the related studies are criticized for lacking in long term results and helping make decisions in GSCM [22]. In this paper, we use quantitative analysis method and provide insights on the effects of factors such as green production, sale channel and green customer on the green level and profitability of GSCM.

Given that better planning and coordination of GSCM practices can generate positive environmental and economic effects, some researchers developed mathematical models to assess the impacts of decision-making and operation of GSC players [23]. Moreover, corporate approaches for performance improvement cannot be undertaken in isolation, so a concerted effort along GSC players is needed [24]. On the other hand, with different profit targets and operation strategies, GSC players can hardly maintain consistency on everything, and sometimes they are in competition with one another. Among all the mathematical methods used in GSCM literature, game theory is highly applicable to the research on the coexistence of competition and cooperation among GSC players.

In the field of GSC logistics, game theory is applied not only to forward logistics but also to reverse logistics whose function are recycling, reusing, and remanufacturing. As a forward logistics example, Barari et al. [25] studied the coordination between the manufacturer and the retailer in an evolutionary game model. They found such coordination could increase environmental benefits and commercial advantages of GSC. As a reverse logistics example, Sheu and Chen [26] applied a three-stage game model to a GSC with both forward and reverse logistics. In addition, low-wholesale-price strategies are suggested for recycling processes under government green subsidization. In this paper, our scope covers only forward logistics of GSC.

We categorize the coexistence of competition and cooperation of GSC players into types of chain and chain, channel and channel, upstream and downstream companies. Jamali and Rasti-Barzoki [12] studied the chain-chain competition of two dual-channel SCs under centralized and decentralized scenarios. They found that the centralized scenario achieves a higher green level of production than the decentralized one does. Chen et al. [27] investigated duopoly GSC with upstream-downstream and channel-channel competition. They explored how manufacturers' market power influences the pricing policies and green strategies. Ghosh and Shah [28] explored the effect of decentralized policy and cooperative policy on the green level of products in a secondary SC composed of a manufacturer and a retailer. The green level is decided individually by the manufacturer in the decentralized policy, while cooperative decisions are made between the upstream and downstream players in the cooperative policy. Then they further put forward a contractual coordination mechanism. In this paper, we focus on the competition and cooperation of channel-channel and upstream-downstream types.

There are many application aspects of game theory to GSCM, such as R&D collaboration, governmental intervention and pricing policy. Dai et al. [29] established Stackleberg game models to study R&D collaboration between GSC members. They revealed that the upstream company generally prefers a Cartelization, while the downstream company mostly favors a non-cooperative scheme. In addition, the Cost-sharing contract generally makes the chain-wide profit get to the summit. Yang and Xiao [30] used game method to explore the governmental interventions in a GSC. They found that with the increase of governmental interventions, the green level of GSC will increase. However, a relatively high green level floor for subsidy causes the first-mover disadvantage of manufacturers. Wei et al. [31] studied the pricing problem in the GSC comprised of two manufacturers and one retailer. In view of the manufacturers' cooperation or noncooperation strategies, they adopted the centralized models and decentralized models. In this paper, we regard prices as decision variables in our game models.

3. Problem Statement and Formulation

3.1. Problem Description

In this paper, we investigate the alignment issues between green level and economic performance of GSC. We are particularly interested to see how the alignment may be achieved through competition and cooperation of the GSC participants. To answer this question, we take into account a dual-distribution GSC composed of a manufacturer, a retailer and customers, as shown in Figure 1. The manufacturer produces green products, which are sold to customers through a retailer or a direct channel. Based on this, four game models are established. Moreover, the effects of green product R&D cost, customer green sensitivity and price sensitivity, are evaluated into the above models by using corresponding coefficients.

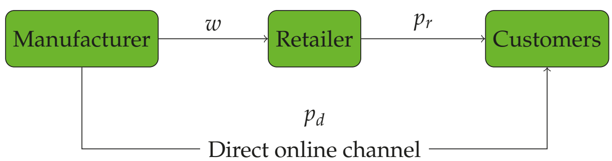

Figure 1. Problem structure.

3.2. Notation

We collect model parameters and decision variables which are used in the four game models. The notations and meanings of them are listed in Table 1.

Table 1. Model parameters and decision variables.

Model Parameter	
D	the market's total potential demand
D_1	the demand in the traditional retail channel
D_2	the demand in the direct channel
c_m	uint production cost of the green product
α	self-price sensitivity coefficient
β	cross-price sensitivity coefficient
r	green sensitivity coefficient
i	green investment coefficient
Decision Variable	
θ	green degree of the green product
w	wholesale price of the green product
p_r	retail price of the green product
p_d	direct price of the green product

3.3. Assumptions

We make the following assumptions, where the parameters and variables are shown in Table 1.

(1) $p_r > w > c_m$. In order to ensure profits for the retailer and the manufacturer, the retail price must be higher than the wholesale price, and the wholesale price higher than the production cost.
(2) $\alpha > \beta > 0$. This indicates that the customers of a given channel are more sensitive to the price changes in this channel than that in the other channel. This assumption is made in many studies, for instance literature [12].
(3) To advance green product R&D, manufacturers need to invest a lot of funds. In addition, the R&D cost is assumed as $i\theta^2$. This type of cost function is considered in many studies, for instance literature [27].
(4) The demand functions of green product in traditional sale channel and online direct channel are as follows, respectively.

$$D_1 = D - \alpha p_r + \beta p_d + r\theta \tag{1}$$

$$D_2 = D - \alpha p_d + \beta p_r + r\theta \tag{2}$$

3.4. The Profit Functions for Each Player

Based on the above assumptions, the manufacturer's profit function is:

$$\pi_m = (w - c_m)D_1 + (p_d - c_m)D_2 - i\theta^2 \tag{3}$$

The retailer's profit function is:

$$\pi_r = (p_r - w)D_1 \tag{4}$$

The total profit function for the supply chain is:

$$\pi_{sc} = (p_r - c_m)D_1 + (p_d - c_m)D_2 - i\theta^2 \tag{5}$$

4. The Model

4.1. Decentralized Scenario

In the decentralized scenario, Stackelberg competition between the manufacturer and the retailer is established. As the leader of the competition, the manufacturer determines the green degree of the product, the wholesale price and the direct price; then, the retailer determines the product's retail price correspondingly. The model is formulated as:

$$\begin{cases} \max \pi_m = (w - c_m)D_1 + (p_d - c_m)D_2 - i\theta^2 \\ s.t. \max \pi_r = (p_r - w)D_1 \end{cases} \tag{6}$$

Theorem 1. *In the decentralized scenario, the optimal green degree, wholesale price, retail price, and direct price are given as follows:*

$$\theta^{M^*} = \frac{r(3\alpha + \beta)(D - \alpha c_m + \beta c_m)}{8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2} \tag{7}$$

$$w^{M^*} = \frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{8}$$

$$p_r^{M^*} = \frac{3\alpha r^2 c_m - 2\alpha^2 i c_m - 6\alpha i D + 2\beta^2 i c_m + \beta r^2 c_m + 2\beta i D}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{9}$$

$$p_d^{M^*} = \frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{10}$$

and the profits of the manufacturer, the retailer and the overall GSC are respectively:

$$\pi_m^{M*} = \frac{-i(3\alpha+\beta)(D-\alpha c_m+\beta c_m)^2}{3\alpha r^2+8\alpha\beta i+\beta r^2-8\alpha^2 i} \tag{11}$$

$$\pi_r^{M*} = \frac{4\alpha i^2(\alpha-\beta)^2(D-\alpha c_m+\beta c_m)^2}{(3\alpha r^2+8\alpha\beta i+\beta r^2-8\alpha^2 i)^2} \tag{12}$$

$$\pi_{sc}^{M*} = \frac{i(D-\alpha c_m+\beta c_m)^2 A}{(3\alpha r^2+8\alpha\beta i+\beta r^2-8\alpha^2 i)^2} \tag{13}$$

The value of A is shown in Appendix A, and the proof of Theorem 1 appears in Appendix B.

4.2. Centralized Scenario

In the centralized scenario, the GSC is regarded as a whole. Instead of making decisions based on their own interests, the manufacturer and the retailer make collective decisions to maximize the overall profits of the GSC. As a result, a high requirement is set for the decision-makers. The model is formulated as:

$$\max \pi_{sc} = (p_r-c_m)D_1+(p_d-c_m)D_2-i\theta^2 \tag{14}$$

Theorem 2. *In the centralized scenario, the optimal green degree, retail price, direct price and the overall profit of the GSC are given as follows:*

$$\theta^* = \frac{r(D-\alpha c_m+\beta c_m)}{2\alpha i-r^2-2\beta i} \tag{15}$$

$$p_r^* = \frac{Di+\alpha c_m i-r^2 c_m-\beta c_m i}{2\alpha i-r^2-2\beta i} \tag{16}$$

$$p_d^* = \frac{Di+\alpha c_m i-r^2 c_m-\beta c_m i}{2\alpha i-r^2-2\beta i} \tag{17}$$

$$\pi_{sc}^* = \frac{i(D-\alpha c_m+\beta c_m)^2}{2\alpha i-r^2-2\beta i} \tag{18}$$

The proof of Theorem 2 appears in Appendix B.

4.3. Revenue-Sharing Scenario

In this section, we establish a retailer-led revenue-sharing contract game model and a bargaining revenue-sharing contract game model. In order to advance the green level of the SC, the profit coordination systems are set up in both models to reduce the manufacturer's burden of the green product R&D. That is, the retailer will return a share of retail profits to the manufacturer. The percentage of retailer gain from retail profits is $\lambda(0<\lambda<1)$, and the percentage of manufacturer gain from retail profits is $1-\lambda$.

4.3.1. Retailer-Led Revenue-Sharing Scenario

In this model, the retailer determines the revenue-sharing ratio λ. The manufacturer determines the wholesale price, the price and the green degree, and then the retailer determines the retail price according to the manufacturer's decision. The model is formulated as:

$$\begin{cases} \max \pi_r = \lambda(p_r-w)D_1 \\ s.t.\max \pi_m = (w-c_m)D_1+(p_d-c_m)D_2-i\theta^2+(1-\lambda)(p_r-w)D_1 \end{cases} \tag{19}$$

Theorem 3. *In the retailer-led revenue-sharing scenario, the optimal revenue-sharing ratio, green degree, wholesale price, retail price and direct price are:*

$$\lambda^{R^*} = \frac{4\alpha\beta i + 2\alpha r^2 - 4\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i} \tag{20}$$

$$\theta^{R^*} = \frac{r(D - \alpha c_m + \beta c_m)(3\alpha^2 i - 2\alpha\beta i - \alpha r^2 - \beta^2 i - \beta r^2)}{B} \tag{21}$$

$$w^{R^*} = \frac{Cc_m + (8\alpha^3 i^2 - 8\alpha^2\beta i^2 - 4\alpha^2 r^2 i + \alpha\beta r^2 i - \beta^2 r^2 i)D}{2\alpha B} \tag{22}$$

$$p_r^{R^*} = \frac{Ec_m + (12\alpha^2 i^2 - 16\alpha\beta i^2 - 5\alpha r^2 i + 4\beta^2 i^2 + \beta r^2 i)D}{2B} \tag{23}$$

$$p_d^{R^*} = \frac{Fc_m + (8\alpha^2 i^2 - 8\alpha\beta i^2 - 3\alpha r^2 i - \beta r^2 i)D}{2B} \tag{24}$$

and the profits of the manufacturer, the retailer and the total supply chain are respectively:

$$\pi_m^{R^*} = \frac{(D - \alpha c_m + \beta c_m)(3\alpha^2 i - 2\alpha\beta i - \alpha r^2 - \beta^2 i - \beta r^2)}{B} \tag{25}$$

$$\pi_r^{R^*} = \frac{i^2(\alpha - \beta)^2(D - \alpha c_m + \beta c_m)^2}{2(r^2 - 2\alpha i + 2\beta i)(\alpha r^2 + \beta r^2 + 4\alpha\beta i - 4\alpha^2 i)} \tag{26}$$

$$\pi_{sc}^{R^*} = \frac{i(D - \alpha c_m + \beta c_m)^2(7\alpha^2 i - 6\alpha\beta i - 2\alpha r^2 - \beta^2 i - 2\beta r^2)}{2B} \tag{27}$$

The values of B, C, E and F are shown in Appendix A, and the proof of Theorem 3 appears in Appendix B.

4.3.2. Bargaining Revenue-Sharing Scenario

In this model, the revenue-sharing ratio λ is determined by the manufacturer and the retailer through bargaining rather than determined by the retailer. The model is formulated as:

$$\max \pi_B = \pi_m \pi_r \tag{28}$$

Theorem 4. *In the bargaining revenue-sharing scenario, the optimal revenue-sharing ratio, green degree, wholesale price, retail price and direct price are:*

$$\lambda^{B^*} = \frac{2\alpha\beta i + \alpha r^2 - 2\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i} \tag{29}$$

$$\theta^{B^*} = \frac{r(D - \alpha c_m + \beta c_m)(10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2)}{3B} \tag{30}$$

$$w^{B*} = \frac{A_1 c_m + (4\alpha^2\beta i^2 - 8\alpha^3 i^2 + 4\alpha^2 r^2 i + 4\alpha\beta^2 i^2 + 2\beta^2 r^2 i)D}{3\alpha B} \tag{31}$$

$$p_r^{B^*} = \frac{B_1 c_m + (16\alpha^2 i^2 - 20\alpha\beta i^2 - 6\alpha r^2 i + 4\beta^2 i^2)D}{2B} \tag{32}$$

$$p_d^{B^*} = \frac{C_1 c_m + (12\alpha^2 i^2 - 12\alpha\beta i^2 - 4\alpha r^2 i - 2\beta r^2 i^2)D}{2B} \tag{33}$$

and the profits of and the profits of the manufacturer, the retailer and the total supply chain are respectively:

$$\pi_m^{B^*} = \frac{i(D - \alpha c_m + \beta c_m)^2(10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2)}{3B} \tag{34}$$

$$\pi_r^{B^*} = \frac{4i^2(\alpha - \beta)^2(D - \alpha c_m + \beta c_m)^2}{9(r^2 - 2\alpha i + 2\beta i)(\alpha r^2 + \beta r^2 + 4\alpha\beta i - 4\alpha^2 i)} \tag{35}$$

$$\pi_{sc}^{B^*} = \frac{i(D - \alpha c_m + \beta c_m)^2(34\alpha^2 i - 32\alpha\beta i - 9\alpha r^2 - 2\beta^2 i - 9\beta r^2)}{9B} \quad (36)$$

The values of A_1, B_1 and C_1 are shown in Appendix A, and the proof of Theorem 4 appears in Appendix B.

5. Model Comparison

Equilibrium solutions of the four models are shown in Table 2.

By comparing and analyzing the equilibrium solutions of the four game models, we draw the following conclusions:

Corollary 1. *The optimal green degrees of the four models in descending order are:* $\theta^* > \theta^{B^*} > \theta^{R^*} > \theta^{M^*}$.

By comparing green degrees of the four models, corollary 1 shows that the optimal green degree is highest in the centralized scenario and lowest in the decentralized scenario. Although the centralized decision model has the best green performance, it is difficult to achieve in reality due to the high requirement for decision-makers. Thus, the two revenue-sharing game models, in which the green degrees are neither the highest nor the lowest, seem to have more practical significance.

Corollary 2. *The sensitivities of the optimal green degrees to parameter r and i are as follows:*

(1) $\frac{\partial \theta^{M^*}}{\partial r} > 0,\ \frac{\partial \theta^*}{\partial r} > 0,\ \frac{\partial \theta^{R^*}}{\partial r} > 0 \text{ and } \frac{\partial \theta^{B^*}}{\partial r} > 0\,;$

(2) $\frac{\partial \theta^{M^*}}{\partial i} < 0,\ \frac{\partial \theta^*}{\partial i} < 0,\ \frac{\partial \theta^{R^*}}{\partial i} < 0 \text{ and } \frac{\partial \theta^{B^*}}{\partial i} < 0\,.$

Corollary 2 shows that the green degree of green product is proportional to customers' green sensitivity, but inversely proportional to green investment coefficient. This indicates that the increase of customers' environmental awareness is a driver for advancing the green level of the product, while R&D cost is a barrier.

Corollary 3. *The optimal retail prices, wholesale prices and direct prices of the four models in descending order are:*

(1) $p_r^{M^*} > p_r^{R^*} > p_r^{B^*} > p_r^*;$

(2) $w^{M^*} > w^{R^*} > w^{B^*};$

(3) $p_d^* > p_d^{B^*} > p_d^{R^*} > p_d^{M^*}.$

The optimal retail price of green products is highest in the decentralized scenario, and lowest in the centralized scenario. The optimal wholesale price is highest in the decentralized scenario, and lowest in the Bargaining revenue-sharing scenario. The optimal direct price is highest in the centralized scenario, and lowest in the decentralized scenario. Given that the centralized model aims at the overall profit of the GSC and does not focus on the profit distribution in GSC, the wholesale price is neglected in Corollary 3.

Corollary 4. *The optimal manufacturer's profit, retailer's profit and the overall profit of the SC in descending order are:*

(1) $\pi_m^{B^*} > \pi_m^{R^*} > \pi_m^{M^*};$

(2) $\pi_r^{R^*} > \pi_r^{M^*} > \pi_r^{B^*};$

(3) $\pi_{sc}^* > \pi_{sc}^{B^*} > \pi_{sc}^{R^*} > \pi_{sc}^{M^*}.$

Table 2. Equilibrium solutions.

	Decentralized Scenario	Centralized Scenario	Retailer-Led Revenue-Sharing	Bargaining Revenue-Sharing
λ	–	–	$\frac{4\alpha\beta i + 2\alpha r^2 - 4\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i}$	$\frac{2\alpha\beta i + \alpha r^2 - 2\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i}$
θ	$\frac{r(3\alpha + \beta)(D - \alpha c_m + \beta c_m)}{8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2}$	$\frac{r(D - \alpha c_m + \beta c_m)}{2\alpha i - r^2 - 2\beta i}$	$\frac{r(D - \alpha c_m + \beta c_m)(3\alpha^2 i - 2\alpha\beta i - \alpha r^2 - \beta^2 i - \beta r^2)}{B}$	$\frac{r(D - \alpha c_m + \beta c_m)(10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2)}{3B}$
w	$\frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i}$	–	$\frac{C c_m + (8\alpha^3 i^2 - 8\alpha^2\beta i^2 - 4\alpha^2 r^2 i + \alpha\beta r^2 i - \beta^2 r^2 i)D}{2\alpha B}$	$\frac{A_1 c_m + (4\alpha^2\beta i^2 - 8\alpha^3 i^2 + 4\alpha^2 r^2 i + 4\alpha\beta^2 i^2 + 2\beta^2 r^2 i)D}{3\alpha B}$
p_r	$\frac{3\alpha r^2 c_m - 2\alpha^2 i c_m - 6\alpha i D + 2\beta^2 i c_m + \beta r^2 c_m + 2\beta i D}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i}$	$\frac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i}$	$\frac{E c_m + (12\alpha^2 i^2 - 16\alpha\beta i^2 - 5\alpha r^2 i + 4\beta^2 i^2 + \beta r^2 i)D}{2B}$	$\frac{B_1 c_m + (16\alpha^2 i^2 - 20\alpha\beta i^2 - 6\alpha r^2 i + 4\beta^2 i^2)D}{2B}$
p_d	$\frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i}$	$\frac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i}$	$\frac{F c_m + (8\alpha^2 i^2 - 8\alpha\beta i^2 - 3\alpha r^2 i - \beta r^2 i)D}{2B}$	$\frac{C_1 c_m + (12\alpha^2 i^2 - 12\alpha\beta i^2 - 4\alpha r^2 i - 2\beta r^2 i^2)D}{2B}$
π_m	$\frac{-i(3\alpha + \beta)(D - \alpha c_m + \beta c_m)^2}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i}$	–	$\frac{(D - \alpha c_m + \beta c_m)(3\alpha^2 i - 2\alpha\beta i - \alpha r^2 - \beta^2 i - \beta r^2)}{B}$	$\frac{i(D - \alpha c_m + \beta c_m)^2(10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2)}{3B}$
π_r	$\frac{4\alpha i^2(\alpha - \beta)^2(D - \alpha c_m + \beta c_m)^2}{(3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i)^2}$	–	$\frac{i^2(\alpha - \beta)^2(D - \alpha c_m + \beta c_m)^2}{2(r^2 - 2\alpha i + 2\beta i)(\alpha r^2 + \beta r^2 + 4\alpha\beta i - 4\alpha^2 i)}$	$\frac{4i^2(\alpha - \beta)^2(D - \alpha c_m + \beta c_m)^2}{9(r^2 - 2\alpha i + 2\beta i)(\alpha r^2 + \beta r^2 + 4\alpha\beta i - 4\alpha^2 i)}$
π_{sc}	$\frac{i(D - \alpha c_m + \beta c_m)^2 A}{(3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i)^2}$	$\frac{i(D - \alpha c_m + \beta c_m)^2}{2\alpha i - r^2 - 2\beta i}$	$\frac{i(D - \alpha c_m + \beta c_m)^2(7\alpha^2 i - 6\alpha\beta i - 2\alpha r^2 - \beta^2 i - 2\beta r^2)}{2B}$	$\frac{i(D - \alpha c_m + \beta c_m)^2(34\alpha^2 i - 32\alpha\beta i - 9\alpha r^2 - 2\beta^2 i - 9\beta r^2)}{9B}$

The values of A, B, C, E, F, A_1, B_1 and C_1 are shown in Appendix A.

The optimal manufacturer's profit is highest in the Bargaining revenue-sharing scenario, and lowest in the decentralized scenario. The optimal retailer's profit is highest in the Retailer-led revenue-sharing scenario, and lowest in the Bargaining revenue-sharing scenario. The optimal overall profit of the GSC is highest in the centralized scenario, and lowest in the decentralized scenario. Corollary 4 indicates that Revenue-sharing game models can attain better economic goals and coordinate participants interest of the GSC.

Corollary 5. *The comparisons of optimal prices and of demands between the traditional channel and the direct online channel are given as follows:*

(1) $p_d^* = p_r^*, \quad p_d^{M^*} < p_r^{M^*}, \quad p_d^{B^*} < p_r^{B^*}, \quad p_d^{R^*} < p_r^{R^*};$
(2) $D_1^* = D_2^*, \quad D_1^{M^*} < D_2^{M^*}, \quad D_1^{B^*} < D_2^{B^*}, \quad D_1^{R^*} < D_2^{R^*}$

In the centralized scenario, the optimal direct price is equal to the optimal retail price. In the other three scenarios, the optimal direct price is less than the optimal retail price. Similarly, in the centralized scenario, the demands in the two channels are equal. In the other three scenarios, the demand in the direct channel is larger than the demand in the traditional channel. With the rapid development of the Internet, the online sale has become a major distribution channel of the GSC.

6. Numerical Analysis

In this section, a numerical example is provided to illustrate the feasibility of the proposed problem solution. Based on the problem assumptions, parameter values are set as: $D = 1000, \alpha = 60, \beta = 30$ and $c_m = 5$.

As shown in Figure 2, the green degree (θ) increases with the increase of the customer green sensitivity coefficient (r), and decreases with the increase of the green investment coefficient (i). Correspondingly, when the customer green sensitivity coefficient is at the maximum and green investment coefficient is at the minimum, the green degree reaches the maximum. These indicate that customers' green sensitivity and preference could promote the improvement of the products' green level, and the high R&D risks may impede such improvement.

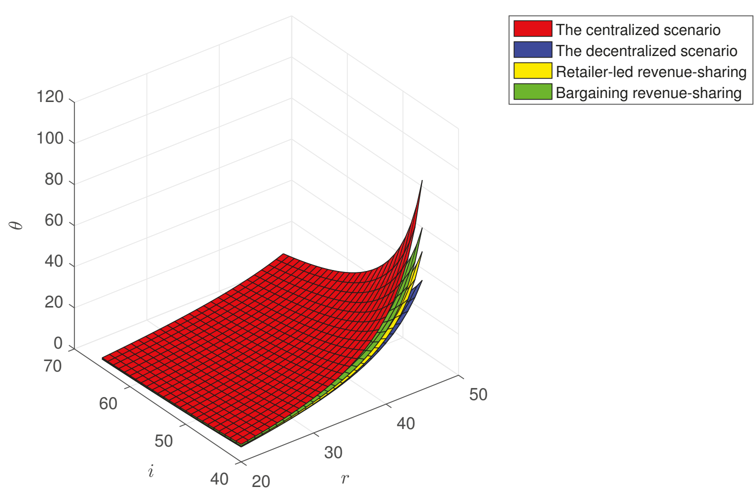

Figure 2. The optimal green degree θ vs r and i.

In Figure 3, The manufacturer's profit (π_m) increases with the increase of the customer green sensitivity coefficient (r), and declines with the increase of the green investment coefficient (i). Correspondingly, when the customer green sensitivity coefficient is at the maximum and green investment coefficient is at the minimum, the manufacturer's profit reaches the maximum. These indicate that customers' sensitivity and preference to green products could increase the profit of the green manufacturer, and the high R&D cost may reduce the profit.

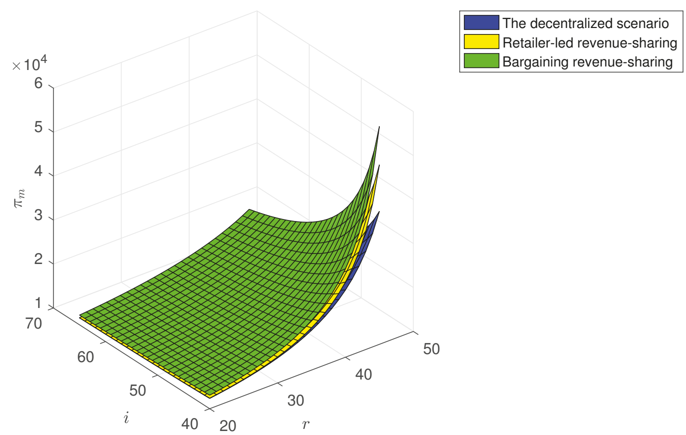

Figure 3. The optimal manufacturer's profit π_m vs r and i.

As shown in Figure 4, the retailer's profit (π_r) increases with the increase of the customer green sensitivity coefficient (r), and decreases with the increase of the green investment coefficient (i). Correspondingly, when the customer green sensitivity coefficient is at the maximum and green investment coefficient is at the minimum, the retailer's profit reaches the maximum. Customer purchasing habits could deeply impact the profit of the retailer. On one hand, customer green consciousness could lead to profit growth. On the other hand, green products R&D may incur higher costs and price, which may drive away price-sensitive customers.

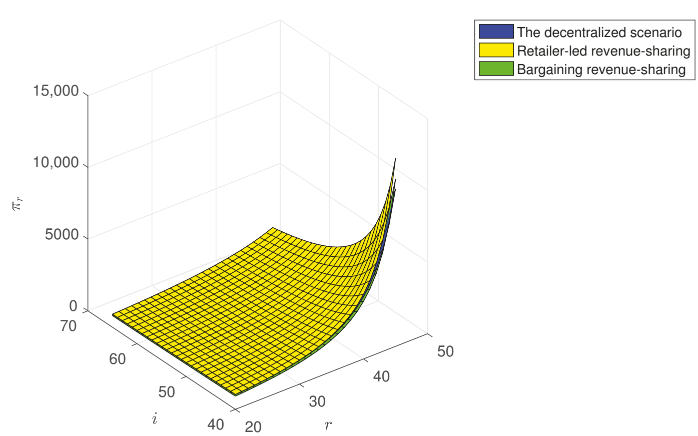

Figure 4. The optimal retailer's profit π_r vs r and i.

In Figure 5, The overall profit of the GSC (π_{sc}) increases with the increase of the customer green sensitivity coefficient (r), and declines with the increase of the green investment coefficient (i). Correspondingly, when the customer green sensitivity coefficient is at the maximum and green investment coefficient is at the minimum, the overall profit of the GSC reaches the maximum. Customer green consciousness could promote the economic performance of the GSC. However, high green products R&D risks may be an impediment.

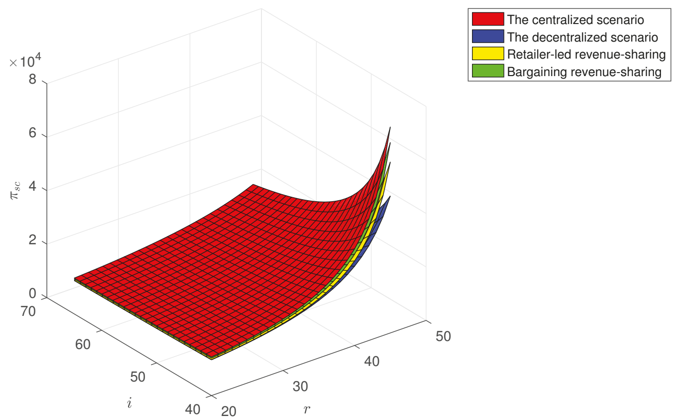

Figure 5. The optimal overall profit π_{sc} vs r and i.

7. Conclusions

In this paper, we investigate the alignment issues between green level and economic performance of GSC. We are particularly interested to see how the alignment may be achieved through competition and cooperation of the GSC participants. To answer this question, we take into account a dual-distribution GSC composed of a manufacturer, a retailer and customers. Based on this, four game models are established, namely decentralized scenario, centralized scenario, retailer-led revenue-sharing scenario and bargaining revenue-sharing scenario. Moreover, coefficients which represent green product R&D cost, customer green sensitivity and price sensitivity, are introduced into the above models. We compared the optimal decisions of the four game models. We also discussed the impact of green sensitivity and green R&D cost. Main findings are summarized as follows:

(1) In terms of green degree and profitability, centralized scenario and the two revenue-sharing scenarios are better than decentralized scenario, which indicates that cooperation between the manufacturer and the retailer is more conducive to the GSC's economic and environmental performance than competition. Given that centralized scenario is difficult to realize due to the high requirement for cooperation level and decision-makers, the two revenue-sharing scenarios are recommended for GSCM practice to achieve the integration of economic and environmental goals.

(2) Driven by the increase of customer green sensitivity, green degree of product will improve, and profits of the manufacturer, the retailer and the overall GSC will rise. In contrast to customer green sensitivity, high green R&D cost is an obstacle for green innovation and profit growth. Therefore, improving green awareness and reducing green R&D cost will raise green level and profitability of the GSC. Since new technologies always come with additional costs, it is difficult to reduce green R&D cost in reality. Consequently, advocating environmental awareness and promoting green consumption are of vital importance to the GSCM practice.

(3) In the centralized scenario, the demands in the two channels are equal. In the other three scenarios, the demand in the direct online channel is larger than the demand in the traditional channel.

These indicate that the Internet has significantly changed consumption patterns and sale modes, and the online sale has become a major distribution channel of the GSC.

This study has several shortcomings. First, our models assume all of the parameters are certain and deterministic. However, uncertainty widely exists in GSC in reality. Thus, introducing uncertainty into our models for future study is worthwhile. Second, our models use linear demand functions, which have some limitations on simulating the complex activities of GSC. Therefore, establishing non-linear demand functions is the future research direction. Finally, this paper takes customer environmental awareness as a driver promoting the implementation of GSCM. Drivers such as investor focuses, environmental policies and government subsidy may also be important and should be considered in our future study.

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Appendix A

$$A = 28\alpha^3 i - 24\alpha^2\beta i - 9\alpha^2 r^2 - 4\alpha\beta^2 i - 6\alpha\beta r^2 - \beta^2 r^2$$

$$B = 8\alpha^3 i^2 - 16\alpha^2\beta i^2 - 6\alpha^2 r^2 i + 8\alpha\beta^2 i^2 + 4\alpha\beta r^2 i + \alpha r^4 + 2\beta^2 r^2 i + \beta r^4$$

$$C = 8\alpha^4 i^2 - 16\alpha^3\beta i^2 - 8\alpha^3 r^2 i + 8\alpha^2\beta^2 i^2 + 3\alpha^2\beta r^2 i + 3\alpha^2 r^4 + 6\alpha\beta^2 r^2 i + 2\alpha\beta r^4 - \beta^3 r^2 i$$

$$E = 4\alpha^3 i^2 - 4\alpha^2\beta i^2 - 7\alpha^2 r^2 i - 4\alpha\beta^2 i^2 + 2\alpha\beta r^2 i + 2\alpha r^4 + 4\beta^3 i^2 + 5\beta^2 r^2 i + 2\beta r^4$$

$$F = 8\alpha^3 i^2 - 16\alpha^2\beta i^2 - 9\alpha^2 r^2 i + 8\alpha\beta^2 i^2 + 6\alpha\beta r^2 i + 2\alpha r^4 + 3\beta^2 r^2 i + 2\beta r^4$$

$$A_1 = -16\alpha^4 i^2 + 36\alpha^3\beta i^2 + 14\alpha^3 r^2 i - 24\alpha^2\beta^2 i^2 - 8\alpha^2\beta r^2 i - 3\alpha^2 r^4 + 4\alpha\beta^3 i^2 - 8\alpha\beta^2 r^2 i - 3\alpha\beta r^4 + 2\beta^3 r^2 i$$

$$B_1 = 8\alpha^3 i^2 - 12\alpha^2\beta i^2 - 12\alpha^2 i r^2 + 6\alpha\beta i r^2 + 3\alpha r^4 + 4\beta^3 r^2 + 6\beta^2 i r^2 + 3\beta r^4$$

$$C_1 = 12\alpha^3 i^2 - 24\alpha^2\beta i^2 - 14\alpha^2 i r^2 + 12\alpha\beta^2 i^2 + 10\alpha\beta r^2 + 3\alpha r^4 + 4\beta^2 r^2 i + 3\beta r^4$$

Appendix B

Proof of of Theorem 1. Using the backward induction method, Equation (4) can be written as:

$$\pi_r = (p_r - w)(D - \alpha p_r + \beta p_d + r\theta) \tag{A1}$$

The second derivatives of p_r is $\frac{\mathrm{d}^2\pi_r}{\mathrm{d}p_r^2} = -2\alpha < 0$, so pi_r is a strictly concave function of p_r. We set the first derivatives of p_r equal to zero, we get:

$$p_r = \frac{D + \beta p_d + r\theta + \alpha w}{2\alpha} \tag{A2}$$

We put Equation (A2) to Equation (3),and get the Hesssian matrix:

$$H(\pi_m) = \begin{bmatrix} \frac{\partial^2\pi_m}{\partial p_d^2} & \frac{\partial^2\pi_m}{\partial p_d \partial w} & \frac{\partial^2\pi_m}{\partial p_d \partial\theta} \\ \frac{\partial^2\pi_m}{\partial w \partial p_d} & \frac{\partial^2\pi_m}{\partial w^2} & \frac{\partial^2\pi_m}{\partial w \partial\theta} \\ \frac{\partial^2\pi_m}{\partial\theta \partial p_d} & \frac{\partial^2\pi_m}{\partial\theta \partial w} & \frac{\partial^2\pi_m}{\partial\theta^2} \end{bmatrix} = \begin{bmatrix} \frac{\beta^2 - 2\alpha^2}{\alpha} & \beta & \frac{(2\alpha+\beta)r}{2\alpha} \\ \beta & -\alpha & \frac{r}{2} \\ \frac{(2\alpha+\beta)r}{2\alpha} & \frac{r}{2} & -2i \end{bmatrix} \tag{A3}$$

The leading principal minors are

$$M_1 = \frac{\beta^2 - 2\alpha^2}{\alpha} \tag{A4}$$

$$M_2 = \frac{2\alpha^3 - 2\alpha\beta^2}{\alpha} \tag{A5}$$

$$M_3 = \frac{-8\alpha^3 i + 3\alpha^2 r^2 + 8\alpha\beta^2 i + 4\alpha\beta r^2 + \beta^2 r^2}{2\alpha} \tag{A6}$$

When $M_1 < 0$, $M_2 > 0$ and $M_3 < 0$, which is $-8\alpha^3 i + 3\alpha^2 r^2 + 8\alpha\beta^2 i + 4\alpha\beta r^2 + \beta^2 r^2 < 0$, the Hessian matrix is negative definite.

By solving $\frac{\partial \pi_m}{\partial p_d} = 0$, $\frac{\partial \pi_m}{\partial w} = 0$ and $\frac{\partial \pi_m}{\partial \theta} = 0$, we get the optimal direct price, the optimal wholesale price and the optimal product green degree:

$$p_d^{M^*} = \frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{A7}$$

$$w^{M^*} = \frac{3\alpha r^2 c_m - 4\alpha^2 i c_m - 4\alpha i D + \beta r^2 c_m + 4\alpha\beta i c_m}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{A8}$$

$$\theta^{M^*} = \frac{r(3\alpha + \beta)(D - \alpha c_m + \beta c_m)}{8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2} \tag{A9}$$

We put Equations (A7)–(A9) into Equation (A2), and get:

$$p_r^{M^*} = \frac{3\alpha r^2 c_m - 2\alpha^2 i c_m - 6\alpha i D + 2\beta^2 i c_m + \beta r^2 c_m + 2\beta i D}{3\alpha r^2 + 8\alpha\beta i + \beta r^2 - 8\alpha^2 i} \tag{A10}$$

We put Equations (A7)–(A10) into Equations (3), (4) and (5), we get $\pi_m^{M^*}$,$\pi_r^{M^*}$ and $\pi_{sc}^{M^*}$. The values are shown in Table 2. □

Proof of Theorem 2. The Hessian matrix obtained from Equation (5) is as follows:

$$H(\pi_{sc}) = \begin{bmatrix} \frac{\partial^2 \pi_{sc}}{\partial p_d^2} & \frac{\partial^2 \pi_{sc}}{\partial p_d \partial p_r} & \frac{\partial^2 \pi_{sc}}{\partial p_d \partial \theta} \\ \frac{\partial^2 \pi_{sc}}{\partial p_r \partial p_d} & \frac{\partial^2 \pi_{sc}}{\partial p_r^2} & \frac{\partial^2 \pi_{sc}}{\partial p_r \partial \theta} \\ \frac{\partial^2 \pi_{sc}}{\partial \theta \partial p_d} & \frac{\partial^2 \pi_{sc}}{\partial \theta \partial p_r} & \frac{\partial^2 \pi_{sc}}{\partial \theta^2} \end{bmatrix} = \begin{bmatrix} -2\alpha & 2\beta & r \\ 2\beta & -2\alpha & r \\ r & r & -2i \end{bmatrix} \tag{A11}$$

The leading principal minors are:

$$M_1 = -2\alpha \tag{A12}$$

$$M_2 = 4\alpha^2 - 4\beta^2 \tag{A13}$$

$$M_3 = 4\alpha r^2 + 8\beta^2 i + 4\beta r^2 - 8\alpha^2 i \tag{A14}$$

When $\alpha r^2 + 2\beta^2 i + \beta r^2 - 2\alpha^2 i < 0$, the Hessian matrix is negative. By solving $\frac{\partial \pi_{sc}}{\partial p_d} = 0$, $\frac{\partial \pi_{sc}}{\partial p_r} = 0$ and $\frac{\partial \pi_{sc}}{\partial \theta} = 0$, we get the optimal product green degree, the optimal retail price and the optimal direct price:

$$\theta^* = \frac{r(D - \alpha c_m + \beta c_m)}{2\alpha i - r^2 - 2\beta i} \tag{A15}$$

$$p_r^* = \frac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i} \tag{A16}$$

$$p_d^* = \frac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i} \tag{A17}$$

We put Equations (A15)–(A17) into Equation (5), and get:

$$\pi_{sc}^* = \frac{i(D - \alpha c_m + \beta c_m)^2}{2\alpha i - r^2 - 2\beta i} \tag{A18}$$

□

Proof of of Theorem 3. The profit functions for the retailer and the manufacturer are as follows:

$$\pi_r = \lambda(p_r - w)D_1 \tag{A19}$$

$$\pi_m = (w - c_m)D_1 + (p_d - c_m)D_2 - i\theta^2 + (1 - \lambda)(p_r - w)D_1 \tag{A20}$$

According to Equations (A19), we get $\frac{\partial^2 \pi_r}{\partial p_r^2} = -2\lambda\alpha < 0$. So Equation (A19) is a strictly concave function of p_r.

By solving $\frac{\partial \pi_r}{\partial p_r 2} = 0$, we can get :

$$p_r = \frac{D + \beta p_d + r\theta + \alpha w}{2\alpha} \tag{A21}$$

We put Equation (A21) into Equations (A20), and get that the Hesssian of Equations (A20) is negative definite. We set the first derivatives of p_d, w and θ equal to zero, we can get:

$$p_d(\lambda) = \frac{(2\alpha r^2 - 2\alpha^2 i c_m - 2\alpha i D + 2\alpha\beta i c_m) - (2\alpha i D + 2\alpha^2 i c_m - \alpha r^2 c_m - \beta r^2 c_m - 2\alpha\beta i c_m)\lambda}{2\alpha r^2 - 4\alpha^2 i + 4\alpha\beta i - (4\alpha^2 i - 4\alpha\beta i - \alpha r^2 - \beta r^2)\lambda} \tag{A22}$$

$$w(\lambda) = \frac{(2\alpha r^2 - 4\alpha^2 i c_m - 2\beta^2 i c_m - 2\beta i D + 6\alpha\beta i c_m) - (4\alpha i D - 2\beta i D - 2\beta^2 i c_m - \alpha r^2 c_m - \beta R^2 c_m)\lambda}{2\alpha r^2 - 4\alpha^2 i + 4\alpha\beta i - (4\alpha^2 i - 4\alpha\beta i - \alpha r^2 - \beta r^2)\lambda} \tag{A23}$$

$$\theta(\lambda) = \frac{2\alpha^2 r c_m - 2\alpha r D - 2\alpha\beta r c_m - (\alpha r D + \beta r D - \alpha^2 r c_m + \beta r c_m)\lambda}{2\alpha r^2 - 4\alpha^2 i + 4\alpha\beta i - (4\alpha^2 i - 4\alpha\beta i - \alpha r^2 - \beta r^2)\lambda} \tag{A24}$$

We put Equations (A22)–(A24) into (A21):

$$p_r(\lambda) = \frac{2\alpha^2 r c_m - 2\alpha^2 i c_m - 2\alpha i D + 2\alpha\beta i c_m - (4\alpha i D - 2\beta i D - 2\beta^2 i c_m \alpha r^2 c_m - \beta r^2 c_m + 2\alpha\beta i c_m)\lambda}{2\alpha r^2 - 4\alpha^2 i + 4\alpha\beta i - (4\alpha^2 i - 4\alpha\beta i - \alpha r^2 - \beta r^2)\lambda} \tag{A25}$$

We put Equations (A22)–(A25) into (A19), and get the second derivatives of λ is less than zero. By setting the first derivatives of λ equal to zero, we get the optimal revenue-sharing ratio:

$$\lambda^{R^*} = \frac{4\alpha\beta i + 2\alpha r^2 - 4\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i} \tag{A26}$$

We put (A26) into (A22)–(A25), and can get:

$$\theta^{R^*} = \frac{r(D - \alpha c_m + \beta c_m)(3\alpha^2 i - 2\alpha\beta i - \alpha r^2 - \beta^2 i - \beta r^2)}{B} \tag{A27}$$

$$w^{R^*} = \frac{Cc_m + (8\alpha^3 i^2 - 8\alpha^2\beta i^2 - 4\alpha^2 r^2 i + \alpha\beta r^2 i - \beta^2 r^2 i)D}{2\alpha B} \tag{A28}$$

$$p_r^{R^*} = \frac{Ec_m + (12\alpha^2 i^2 - 16\alpha\beta i^2 - 5\alpha r^2 i + 4\beta^2 i^2 + \beta r^2 i)D}{2B} \tag{A29}$$

$$p_d^{R^*} = \frac{Fc_m + (8\alpha^2 i^2 - 8\alpha\beta i^2 - 3\alpha r^2 i - \beta r^2 i)D}{2B} \tag{A30}$$

Then we can get $\pi_m^{R^*}$,$\pi_r^{R^*}$ and $\pi_{sc}^{R^*}$. The values are shown in Table 2. □

Proof of Theorem 4. We put (A22)–(A25) into (A19) and (A20), and can get:

$$\pi_B(\lambda) = \frac{4\alpha i^3 \lambda(\alpha-\beta)^2 (D - \alpha c_m + \beta c_m)^4}{(4\alpha^2 i + 4\alpha^2 i\lambda - 2\alpha r^2 - \alpha r^2 \lambda - \beta r^2 \lambda - 4\alpha\beta i - 4\alpha\beta i\lambda)^3} \tag{A31}$$

Similarly, we get the first and second derivatives of λ for the Equation (A31). By solving $\frac{\mathrm{d}\pi_B}{\mathrm{d}\lambda} = 0$, we can get:

$$\lambda^{B^*} = \frac{2\alpha\beta i + \alpha r^2 - 2\alpha^2 i}{4\alpha\beta i + \alpha r^2 + \beta r^2 - 4\alpha^2 i} \tag{A32}$$

We put (A32) into the previous expressions, and get θ^{B^*}, w^{B^*}, $p_d^{B^*}$,$p_r^{B^*}$, $\pi_m^{B^*}$, $\pi_r^{B^*}$ and $\pi_{sc}^{B^*}$. The values are shown in Table 2. □

Proof of Corollary 1. $\because \pi_{sc}^* = \frac{i(D - \alpha c_m + \beta c_m)^2}{2\alpha i - r^2 - 2\beta i} > 0$ and $i > 0$

$\therefore 2\alpha i - r^2 - 2\beta i > 0$

$\because \theta^* = \frac{r(D - \alpha c_m + \beta c_m)}{2\alpha i - r^2 - 2\beta i} > 0, r > 0$

$\therefore D - \alpha c_m + \beta c_m > 0$

$\because \theta^{M^*} = \frac{r(3\alpha + \beta)(D - \alpha c_m + \beta c_m)}{8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2} > 0 \therefore 8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2 > 0$

$\because 2\alpha^2 i - 2\beta^2 i - \alpha r^2 - \beta r^2 > 0, \alpha > \beta \therefore 2\alpha^2 i - 2\beta^2 i - 2\beta r^2 > 0$

$\therefore 10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2 = (8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2) + (2\alpha^2 i - 2\beta^2 i - 2\beta r^2) > 0$

$\because \theta^{B^*} = \frac{r(D - \alpha c_m + \beta c_m)(10\alpha^2 i - 8\alpha\beta i - 3\alpha r^2 - 2\beta^2 i - 3\beta r^2)}{3B} > 0$

$\therefore B > 0$

$\therefore \theta^* - \theta^{B^*} = \frac{2ri(\alpha-\beta)^2(D - \alpha c_m + \beta c_m)}{3B} > 0$, i.e., $\theta^* > \theta^{B^*}$

Similarly, $\theta^{B^*} > \theta^{R^*}$ and $\theta^{R^*} > \theta^{M^*}$. □

Proof of Corollary 2. $\because \alpha > \beta \therefore r^2 + 2\alpha i - 2\beta i > 0$

$\therefore \frac{\partial \theta^*}{\partial r} = \frac{(r^2 + 2\alpha i - 2\beta i)(D - \alpha c_m + \beta c_m)}{(r^2 - 2\alpha i + 2\beta i)^2} > 0$

Similarly, $\frac{\partial \theta^{M^*}}{\partial r} > 0$, $\frac{\partial \theta^{R^*}}{\partial r} > 0$, $\frac{\partial \theta^{B^*}}{\partial r} > 0$, $\frac{\partial \theta^*}{\partial i} < 0$, $\frac{\partial \theta^{M^*}}{\partial i} < 0$, $\frac{\partial \theta^{R^*}}{\partial i} < 0$ and $\frac{\partial \theta^{B^*}}{\partial i} < 0$. □

Proof of Corollary 3. $\because D - \alpha c_m + \beta c_m > 0, B > 0, 2\alpha i - r^2 - 2\beta i > 0, 8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2 > 0$

$\therefore p_r^{M*} - P_r^{R^*} = \frac{ir^2(\alpha-\beta)^2(D - \alpha c_m + \beta c_m)(4\alpha i - 2r^2 - 4\beta i)}{2B(8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2)} > 0$, i.e., $p_r^{M*} > P_r^{R^*}$

Similarly, $p_r^{R*} > P_r^{B^*}$ and $p_r^{B*} > P_r^*$

In summary, $p_r^{M*} > P_r^{R^*} > p_r^{B^*} > p_r^*$

We can get $w^{M^*} > w^{R^*} > w^{B^*}$ and $p_d^* > p_d^{B^*} > p_d^{R^*} > p_d^{M^*}$ likewise. □

Proof of Corollary 4. $\because B > 0$

$\therefore \pi_m^{B^*} - \pi_m^{R^*} = \frac{i^2(\alpha-\beta)^2(D - \alpha c_m + \beta c_m)^2}{3B} > 0$, i.e., $\pi_m^{B^*} > \pi_m^{R^*}$

Similarly, $\pi_m^{R^*} > \pi_m^{M^*}$

In summary, $\pi_m^{B^*} > \pi_m^{R^*} > \pi_m^{M^*}$

We can get $\pi_r^{R^*} > \pi_r^{M^*} > \pi_r^{B^*}$ and $\pi_{sc}^* > \pi_{sc}^{B^*} > \pi_{sc}^{R*} > \pi_{sc}^{M*}$ likewise. □

Proof of Corollary 5. $p_d^* = \dfrac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i}$ and $p_r^* = \dfrac{Di + \alpha c_m i - r^2 c_m - \beta c_m i}{2\alpha i - r^2 - 2\beta i}$

$\therefore p_d^* = p_r^*$
$\therefore D_1^* - D_2^* = (\alpha + \beta)(p_d^* - p_r^*) = 0$
$\therefore D_1^* = D_2^*$
$\because 8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2 > 0, D - \alpha c_m + \beta c_m > 0, \alpha - \beta > 0, i > 0$
$\therefore p_d^{M*} - p_r^{M*} = \dfrac{-2i(\alpha - \beta)(D - \alpha c_m + \beta c_m)}{8\alpha^2 i - 3\alpha r^2 - 8\alpha\beta i - \beta r^2} < 0$, i.e., $p_d^{M*} < p_r^{M*}$
$\because\ D_1^{M*} - D_2^{M*} = (\alpha + \beta)(p_d^{M*} - p_r^{M*}) < 0$
$\therefore D_1^{M*} < D_2^{M*}$
Similarly, $p_d^{R^*} < p_r^{R^*}, p_d^{B^*} < p_r^{B^*}, D_1^{R^*} < D_2^{R^*} and D_1^{B^*} < D_2^{B^*}$. □

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Role of Information and Communication Technology in Green Supply Chain Implementation and Companies' Performance

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Abstract: The aim of this study is to quantify the impact of information and communication technologies (ICT) and its technological updates on the success of the green supply chain (GSC) implementation, as well as the benefits this affords. This research is applied to the Mexican maquiladora export industry. A model of structural equations is presented to know the importance of the integration of ICT, combined with the implementation of GSC and the generation of benefits with the use of ICT. The results indicate that there is a direct, positive effect (PE) and significant among the four latent variables (LTV) analyzed but the most noteworthy is the indirect effect that the variable updating the ICT has on the benefits of GSC, through the variable mediators' implementation of a GSC, since the direct effect of updating the ICT on the benefits of the implementation of GSC does not become significant. Whereby, it is recommended that the industry integrates and updates its ICT since, using the integrated and updated ICT and the implementation of a GSC, a series of economic, productive and environmental benefits will be created.

Keywords: information and communication technologies; green supply chain; update and sustainable

1. Introduction

Nowadays, organizations must always ensure they consider their environmental impact. Not doing so makes their business outsiders, as the concepts of environmental and social sustainability are becoming increasingly popular amongst organizations, providers, distributors and clients. Adopting a more respectful approach to the environment is now an obligation, not a choice [1]. Organizations develop diverse business strategies but the important and most widely-used is that of the green supply chain (GSC) [2]. GSCs allow a balance between ecological, financial and social benefits, as well as provide a solution to environmental problems and image generated by the different activities which make up the traditional supply chain (SC) [3].

A GSC is a coupling of environmental thinking and traditional SC management [4], which involves several phases in the life of a product: design, selection and material supply, manufacturing processes, integrating information communication technology (ICT), delivering the final product to the consumer and its evaluation at the end of its life-cycle [5,6]. That is, the GSC is the generation of green purchases, green manufacturing, green packaging, the adoption of green technology, green distribution and green marketing, what it is being looked for, trying to eliminate or minimize waste in the form of hazardous, chemical, energy, emission and solid waste [6–8]. By adopting a GSC, companies improve their image and social acceptance and they generate higher financial income and so forth.

However, implementing a GSC is no easy task, because it requires a flexible, agile, robust and sustainable design, with long-term results for its procedures, products and green logistics systems [2]. To facilitate the GSC implementation process, companies are integrating ICT into their SC [9,10].

In this context, the use of ICT in the implementation of a GSC requires: the development of information systems, manufacturing which is service focused, intelligent products, robust product testing, environmental intelligence, optimization, energy awareness and auto-organized systems for environmental monitoring [11]. These technologies were inconceivable in the past but have currently helped to provide versatile solutions to the challenges faced in a GSC [12].

All the above shows a tendency towards 'green' supply chains and the implementation of ICT has been a great help in speeding up this process and in obtaining the benefits that that philosophy offers [13]. Therefore, the aim of this study is to quantify the effect ICT and its technological updates has on the success of the implementation of a GSC, as well as the benefits this affords. The results obtained from this research will allow the people responsible for SCs to identify the importance of ICT in the successful implementation of the GSC philosophy and its benefits. It will also make possible the identification of important aspects of those that are trivial in the functioning of GSCs.

2. Hypotheses and Literature Review

2.1. Integrating and Updating ICT in a GSC

ICTs are technologies which were originally meant to support the exchange of information but in modern-day life ICTs are playing an increasingly important role in our day to day life as humans [14]. Said activities include collating, processing, storing and exchanging information quickly and easily, as well as offering alternative methods in which to work, improving supply chains, controlling transport, energy supply and so forth [15]. In fact, these examples are widely used in predictions about our future, as there are more and more activities which involve more efficient communication and collaboration systems. ICTs have a role to play within the production process, financial management, the relationship with providers, clients and they are considered a vital source of competitiveness and innovation in sustainable industrial systems [12,16].

One of the main advantages offered by ICT in SCs is the exchange of information (EI) in real time and proper form, via the use of intelligent communication networks, such as internet, intranet, Enterprise Resource Planning (ERP), Customer Relationship Management (CRM) and others. Another benefit is that they are used by all members of the SC and can improve the efficiency and the number of eco-friendly practices as well as reduce costs and the need for inventories [11]. ICT has radically and efficiently transformed a great deal of production and transport processes. It allows for the virtualization of products, the digitalization of information, the de-materialization of transport and a reduction in storage space [17].

There are many studies which state that the EI increases the level of service and reduces the time involved in a GSC cycle. All of this affects general expenses, chain inventories, transport and storage costs [11]. It also makes it possible to improve the strategic order of the SC components, feedback and exchange of information in real-time with clients and providers. This means that predictions for demand and production planning are more real and precise.

Besides, the application of updating ICT of a high technological update is considered a powerful tool in the improvement of companies. It allows for an improvement in energy efficiency and EI in many financial sectors. ICT currently provides efficient technical support for environmental monitoring in real time, the management of natural resources and emissions evaluations. The way in which ICT is applied has evolved and makes it possible to reach the environmental objectives of a GSC, whilst also creating value for the market, as well as being a competitive advantage [18]. Not all ICTs have the same benefits however and it all depends on how up-to-date and innovative they are. The impact of ICT is reflected in two ways: ecological product innovation (which provides clients with new ecological products) and innovation in ecological procedures (green production process) [19]. Having taken the above into consideration, we suggest the next hypothesis:

Hypothesis 1. (H_1) *The integration of ICT has a direct and positive effect on updating ICT within a GSC.*

2.2. The Implementation of GSC

A GSC is a network made up of providers, producers, storage facilities and distributors who work together to turn their plans, activities and raw material into a final product. This SC must also include an environmental outlook across all stages [20]. When it comes to implementing a GSC, the use of ICT is important to try and improve the sustainability of the company's communication, provisioning and transport systems, all of which allows for client and provider involvement (external part of the company's business). This coordination via ICT means that procedures, products and communication via the EI can be better integrated, whilst also minimizing the cost and environmental impact.

A successful implementation of ecological ICTs also contributes to the correct implementation of the GSC. Costs are reduced, relationships between members are improved, the flow of materials increases, deliveries are faster, client satisfaction improves and, what is most important, an environmentally-friendly outlook is reinforced across the entire SC [21]. By implementing the GSC, the use of a unified system and a centralized control system such as ICT, companies improve their inverse logistics with the design of ecological products and procedures. With the aim of determining whether the integration of ICTs facilitates the implementation of a GSC, we suggest the next hypothesis:

Hypothesis 2. (H_2) *The integration of ICT has a direct and positive effect on the implementation of GSC.*

By implementing a GSC, organizations can minimize and eliminate the negative effects that a SC has on the environment, as well as improve the company's technological or innovative standards. Similarly, ICT must have a positive impact on the environment and produce a PE on the design and processes of eco-products [5]. In order to innovate the GSC technologically the organization must invest in updating of ICT which is able to design products ecologically and monitor production and distribution systems [22], taking into account the fact that these could become obsolete in a very short period of time.

Investment in ICT is currently linked to business growth as well as to the growth of the world's economy [23]. There are specific cases that compare the benefits and productivity obtained by companies of different technological updates (with different levels of up-to-datedness) and those using recently created technologies show a clear advantage [24,25]. Considering that how up-to-date the ICT that an organization uses, as well as its technological updates, have a role to play in company operations and their SC, we suggest the next hypothesis:

Hypothesis 3. (H_3) *Updating of ICT has a direct and positive effect on the implementation of GSC.*

2.3. Benefits of the Implementation of GSC

In a GSC implementation, ICTs have been identified as one of the main forces when it comes to facilitating the process of obtaining social, economic and operative benefits [26]. Nevertheless, we must not forget that the aim of a GSC must be to subject all of an organizations' activities to strict environmental demands and technological innovations in its processes and products, with the objective of maximizing the growth of its income, investment and corporate image [21].

As above mentioned, one of ICT's most valuable resources is EI, as it facilitates a whole list of benefits. These include products which are better adjusted to consumer demand, a reduced need for inventories, the ability to anticipate market changes to reduce transport and increase sales, the ability to respond quickly and detect problems in their early stages to reduce any losses and so forth [24,27].

A successful EI shows three potential advantages for producers: a reduction in costs, a reduction in inventory and a reduction in their environmental impact [28]. Partners and participants in the implementation project can benefit from: changing their existing plans, formulating future operations, improving their efficiency, reducing transport, reducing environmental costs and improving their customer service. Having taken the above into consideration, the following hypothesis is proposed:

Hypothesis 4. (H_4) *The integration of ICT has a direct and positive effect when it comes to obtaining benefits from the GSC when it is implemented.*

Updating of ICT and a good general technological standard allow for a fast and easy EI between the GSC components, integrating both internal and external business functions [6]. The return on investment also increases thanks to innovation in procedures, as do sales. The EI and ICTs have served to demonstrate the importance of SCs, GSCs and updating of ICTs has also been identified as a key factor in order to achieve environmental sustainability as they facilitate: information line-up and planning, organizational environmental practices, the capacity to improve and allow for an effective compliance with environmental requirements [26]. Having taken the above into consideration, the following hypothesis is proposed:

Hypothesis 5. (H_5) *Updating of ICT has a direct and positive effect when it comes to obtaining benefits from the GSC once implemented.*

Implementing a GSC in an organization entails a series of benefits, as this process is crucial to promote green-thinking within an organization. Organizations currently have to maintain adequate levels of competitiveness whilst also following government, environmental and social requirements [29,30]. Compliance with these types of regulations is essential when it comes to carrying out proactive ecological strategies, needed to achieve environmental goals and an improved business image. To successfully implement a GSC, however, it is fundamental that providers and customers take an active part [31,32]. Solid partnerships with providers and customers help in the adoption and development of innovative and environmentally-friendly technologies. Having taken the above into consideration, the next hypothesis is proposed:

Hypothesis 6. (H_6) *The implementation of GSC has a direct and positive effect when it comes to obtaining benefits from the GSC when it is implemented.*

Figure 1 shows the association between the variables analyzed in this study; it indicates the number of items in each, which is discussed in the Methodology section of this manuscript.

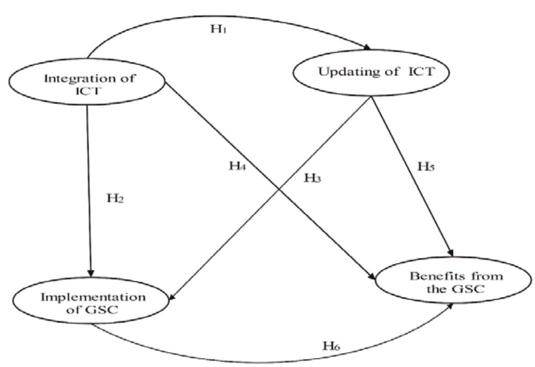

Figure 1. Hypothesis.

3. Development of Methodology

3.1. Phase 1. Sample Collection

To collect information and validate the model in Figure 1, a designed questionnaire has been used, one of the most used methods to gather information easily and quickly [33–35], as well as a deep revision of literature, which allows us to identify research related to the integration and updating of IT, the implementation and the benefits of a GSC, all considered LTV. The literature revisions a rational validation of the questionnaire and identifies the items.

Given that the questionnaire items were obtained from research carried out in different countries and industrial sectors, a group of green supply chain experts, including academics and engineers working in companies, evaluated the congruence, relevance, importance and language. This process represents a judges' validation and helped to adapt it to the context of the maquiladora industry [36,37].

The final questionnaire is divided into two parts. The first part is composed of twelve LTV, of which only four were taken to develop this research, defined as the LTV in Figure 1 and the items appear in Table 1. The items were responded to on a Likert scale with values of one to five, where one indicates very low or never and five indicates very high or always. The second section is a series of demographic questions such as the respondent's position, years of experience and so forth, which will help us characterize the sample.

Table 1. Items in the LTV.

Integration of ICT	Acronym
Use of ERP, CRM and Intranet with providers [12,19]	ITI1
EI is used in real-time with providers [11,19]	ITI2
There is an improved ICT line-up with providers [11,17]	ITI3
Use of EI across the entire organization [11,18]	ITI4
Use of ERP, CRM and Intranet with clients [12,19]	ITI5
Use of EI via ICT with clients [11,38]	ITI6
Improved ICT line-up with intelligent products [12,38]	ITI7
Feedback across all levels via ICT [18,19]	ITI8
Use of ICT in predictions with providers [11,17]	ITI9
Updating of ICT	
Use of the most up-to-date ecological ICTs [17,18]	UTI1
More modern ICT than the competitors [12,19]	UTI2
Investment in ICT to align their technology with that of its partners [12,19]	UTI3
Implementation of GSC	
Work on the product's life cycle (inverse logistics) [32,39]	IGSC1
GSC is considered a priority strategy [16,26]	IGSC2
Implement indicators to measure environmental impact [18,40]	IGSC3
Green initiatives are backed by superior management [39,40]	IGSC4
Savings are generated because of the GSC in energy, transport, storage and packaging [11,18]	IGSC5
The company's performance is better than its competitors when it comes to managing the GSC [8,41]	IGSC6
Environmentally-friendly products are designed [5,16]	IGSC7
Green initiatives are invested in even if they do not generate a return on investment (ROI) [8,42]	IGSC8
Green initiatives are evaluated over the entire SC [17,39]	IGSC9
Benefits from the GSC	
Reduced costs [9,11]	BGSC1
Increased sales [5,42]	BGSC2
Customer satisfaction [26,43]	BGSC3
Better ROI [5,11]	BGSC4
Increase in income [8,42]	BGSC5
Reduction in emissions/waste [11,40]	BGSC6
Improved business image [5,26]	BGSC7
Increase income through ecological products [5,16]	BGSC8
Product innovation [40,41]	BGSC9

The questionnaire is applied to the Mexican Maquiladora export industry, focusing on staff with at least one-years' experience on their job, so that the sampling is stratified into different categories. We set up appointments with managers to apply the questionnaire in a personal interview and the respondents later recommended the questionnaire to their colleagues and then a snowball sampling followed.

3.2. Phase 2. Capture and Debugging the Sample

The information is processed using statistic software called SPSS 24® and data is de-bugged with the aim of detecting atypical values and any missing values. These are replaced by the value of the median for each item due to its ordinal values [44]. In addition, we calculate the standard deviation in each case of the questionnaires applied to identify respondents who are not committed, where cases of values of lower than 0.500 on the standard deviation are eliminated [45].

3.3. Phase 3. Definition of LTV

Although the LTV in the questionnaire had already defined a list of items that integrated them, to demonstrate statistically that there was an association between the dimension and the items, a factorial analysis of the four variables analyzed was developed. A promax rotation is used to continue with the analysis of structural equations models and the factorial loads and the associated p-values of each item are analyzed. In this case, it is sought that the factorial loads are greater than 0.5 and that the p associated value is less than 0.05 [46,47].

3.4. Phase 4. Characterization of the Items

We carry out a characterization of the items which make up every of the LTV. We use the interquartile range (IR) as a measure of dispersion of the data, so the first and third quartile of data is calculated. High values specify that there is no consensus between the respondents in relation to the true value that that item should have but if the value is low, it specifies a consensus on its value [48]. The median is also used as a measure of central tendency and high values indicate that the respondents consider that item to be very important, while low values specify that the item is not very important to them [49].

3.5. Phase 5. Characterization of the Sample

Crossed tables are used for analysis on demographic data. These tables will serve to characterize the sample in terms of the gender of responders, the industrial sector to which they belong, the years of experience and the job position. These tables help to determine the level of experience that the respondents had and, therefore, the reliability of the information obtained, as well as to identify tendencies in responders.

3.6. Phase 6. Statistical Validation

For the statistical validation for the LTV in the model, we have used different indices, such as:

1. Average Variance Extracted (AVE) to determine the convergent validity, for which values of over 0.5 were expected [50].
2. Cronbach's Alpha and the reliability index to determine the reliability on the scale and values of over 0.7 are expected [51].
3. Full collinearity VIF to identify vertical and lateral collinearity, for which values lower than 5 are expected [52].
4. R-squared and R-squared adjusted to measure parametric predictive validity.
5. Q-squared to measure non-parametric predictive validity [52].

3.7. Phase 7. Design of Structural Equations Modelling

The model in Figure 1 is assessed by means of structural equations based on partial least squares (PLS), a multi-variate analysis technique used and applied in diverse research areas for example biology, medicine and engineering [53]. The software used to simulate the model is WarpPLS 5.0®, the algorithms of which are based on PLS and the use of which is recommended in small samples, unusual data or data obtained by means of a Likert scale [54].

Several efficiency indices are analyzed before the model interpretation, for example: average path coefficient (APC) to test the hypotheses, the average R-squared (ARS), average adjusted R-squared (AARS) for predictive validity, average variance inflation factor (AVIF) and average full collinearity VIF (AFVIF) for collinearity and the Tenenhaus GoF for data fit. The study established 0.05 as a maximum cut-off p-value for these indices; thus, inferences were made with a 95% confidence level, testing the null hypothesis that APC and ARS are equal to zero, versus the alternative hypothesis stating that APC and ARS are different to zero.

Three different types of effects are analyzed in the model; (1) direct effects (appearing in Figure 1 as arrows from an LTV to other); (2) indirect effects (given by paths with two or more segments); and (3) total effects (the sum of direct and indirect effects). Also, in order to determine their significance, the p-values were analyzed by comparing the null hypothesis $\beta i = 0$, versus the alternative hypothesis $\beta i \neq 0$ [55].

4. Results

4.1. Descriptive Analysis of the Sample

The survey is applied for 6 months and 326 questionnaires were obtained, of which only 284 were valid for the analysis after performing the debugging of the database, where 42 were eliminated because they contained missing data or uninvolved respondents were detected. Table 2 shows the crossed table, which compares the industrial sector and gender of the interviewees; first, it is observed that there was more participation from men than women, with a total participation of 194 men, who represent the 68.30% of the total sample and only 90 women, representing 31.69%. Likewise, it can be observed that 198 (69.71%) of the interviewees are from the two industrial sectors, 119 belonging to the automotive sector and 79 to the electrical/electronic sector.

Table 2. Industrial sector and gender.

Sector	Gender		Total
	Male	Female	
Automotive	77	42	119
Electric/Electronic	56	23	79
Other	15	8	23
Medical	13	6	19
Metalworking	13	3	16
Plastics	9	2	11
Communications	6	2	8
Textile	3	2	5
Services	2	2	4
Total	194	90	284

Table 3 shows the crossed table, which compares the position of the interviewees and their years of experience. It can be seen that 213 of the interviewees have a high hierarchical position, 139 are engineers and 74 are managers. Table 3 also indicates that 242 interviewees, that is 85.21%, have more than two years of experience in their position, which will help us validate the information obtained based on the experience of the interviewees.

Table 3. Job position and years of experience.

Job Position	Years of Experience					Total
	>1–<2	>2–<3	>3–<4	>4–<5	>5	
Engineer	12	23	18	36	56	139
Manager	2	4	11	22	35	74
Storekeeper	4	5	6	10	18	43
Technician	13	2	7	4	2	28
Total	42	51	31	25	135	284

4.2. LTV Generation

Table 4 illustrates the factorial analysis for the 30 items analyzed in the four latents. The factor loading of each item in all the LTV is illustrated and in the last column appears the *p* value for the statistical test of significance. Given that the factorial loads are greater than 0.5 in all the items and that the *p* value is less than 0.001, it is concluded that all the items have convergent validity in the variable that has initially been proposed, allowing to proceed to the model analysis.

Table 4. Factor loadings.

Items	LTV				*p*-Value
	Integration of ICT	Updating of ICT	Implementation of GSC	Benefits from the GSC	
ITI1	*0.759*	0.058	−0.141	0.134	<0.001
ITI7	*0.8*	−0.063	−0.035	−0.01	<0.001
ITI8	*0.809*	0.188	0.007	−0.003	<0.001
ITI9	*0.74*	0.095	0.016	0.022	<0.001
ITI2	*0.773*	−0.029	−0.105	0.081	<0.001
ITI3	*0.806*	0.002	0.157	−0.072	<0.001
ITI4	*0.763*	−0.051	0.088	−0.096	<0.001
ITI5	*0.808*	−0.051	−0.011	−0.012	<0.001
ITI6	*0.818*	−0.141	0.015	−0.036	<0.001
UTI1	−0.02	*0.91*	−0.066	0.056	<0.001
UTI2	0.051	*0.922*	0.075	−0.071	<0.001
UTI3	−0.031	*0.922*	−0.01	0.016	<0.001
IGSC2	−0.141	0.191	*0.856*	−0.018	<0.001
IGSC4	−0.039	0.04	*0.885*	−0.039	<0.001
IGSC6	0.065	−0.035	*0.905*	−0.034	<0.001
IGSC7	0.087	−0.131	*0.875*	0.033	<0.001
IGSC1	0.062	−0.06	*0.825*	−0.105	<0.001
IGSC3	−0.014	−0.004	*0.866*	0.043	<0.001
IGSC5	−0.044	−0.002	*0.84*	0.139	<0.001
IGSC8	0.142	−0.207	*0.869*	0.023	<0.001
IGSC9	−0.125	0.217	*0.838*	−0.042	<0.001
BGSC9	−0.065	0.061	0.024	*0.844*	<0.001
BGSC1	0.068	−0.044	−0.184	*0.844*	<0.001
BGSC7	−0.106	0.05	0.048	*0.831*	<0.001
BGSC5	−0.062	0.004	−0.185	*0.854*	<0.001
BGSC8	−0.063	−0.024	0.043	*0.808*	<0.001
BGSC4	0.064	−0.011	0.046	*0.835*	<0.001
BGSC6	−0.013	0.115	0.186	*0.852*	<0.001
BGSC2	−0.012	0.06	−0.089	*0.817*	<0.001
BGSC3	0.196	−0.222	0.116	*0.801*	<0.001

4.3. Characterization of the Items

The descriptive analysis of the items appears in Table 5 and is shown in descending order in accordance with the median value from the second column. We can see that 29 out of the total 30 items have a median greater than 4, which means that, according to the participants' perception, these items are the most significant and the ones they associate the most with the *Integration of ICT*, *Updating of ICT* and the GSC and that they can come to have a greater impact on their implementation. Finally, in the third column we can see the IR as a measure of dispersion.

Table 5. Characterization of the items.

Items Integration of ICT	Median	IR
ITI1	4.788	1.971
ITI5	4.607	2.003
ITI7	4.485	1.959
ITI9	4.470	2.093
ITI2	4.467	1.953
ITI8	4.396	1.979
ITI3	4.364	2.006
ITI6	4.273	2.024
ITI4	4.272	2.119
	Updating of ICT	
UTI3	4.364	2.076
UTI1	4.327	2.075
UTI2	4.268	2.055
	Implementation of GSC	
IGSC3	4.361	2.040
IGSC7	4.318	2.094
IGSC5	4.307	2.211
IGSC9	4.207	2.128
IGSC1	4.187	2.027
IGSC6	4.169	1.983
IGSC2	4.131	2.039
IGSC4	4.056	2.066
IGSC8	3.961	2.194
	Benefits from the GSC	
BGSC2	4.865	1.762
BGSC1	4.702	1.972
BGSC7	4.700	2.019
BGSC6	4.664	2.025
BGSC9	4.625	2.003
BGSC4	4.497	2.011
BGSC5	4.483	2.107
BGSC8	4.322	2.096
BGSC3	4.136	1.659

4.4. Validation of LTV

The indices for validating LTV integrated in the model in Figure 1 appear in Table 6. We can see that the coefficients R-squared, adjusted R-squared and Q-squared are presented only for dependent LTV and that the values mentioned above are acceptable, as they are greater than 0.02, which means that the model has an adequate predictive validity (parametric and non-parametric). Similarly, the average variance extracted (AVE) is shown. We can see that all the LTV have values close to, or greater than 0.5, which specifies that the model has an acceptable convergent validity.

The reliability index and the Cronbach's Alpha coefficients are calculated for all LTV and it is observed that those values are greater than 0.7, so it is concluded that the LTV have an internal validity. Finally, we observe that all the LTV analyzed have a VIF value lower than 3.3, which specifies that there are no collinearity issues.

Table 6. Validation of LTV.

LTV Coefficients	Integration of ICT	Updating of ICT	Implementation of GSC	Benefits from the GSC
R-squared		0.526	0.412	0.599
Adj. R-squared		0.524	0.408	0.595
Q-squared		0.526	0.414	0.600
Avg. var. extract.	0.619	0.843	0.744	0.692
Cronbach's alpha	0.923	0.907	0.957	0.944
Composite reliab.	0.936	0.942	0.963	0.953
Full collin. VIF	2.358	2.475	2.457	2.463

4.5. Structural Equations Model

The model's results are shown in Figure 2, where each segment shows the association between two LTV and is shown using the β parameter and the p-value, while R-squared is used to measure the variance quantity explained in dependent variables, as well as indicating the combined loadings and the cross-loadings to determine the convergent validity of each of the items.

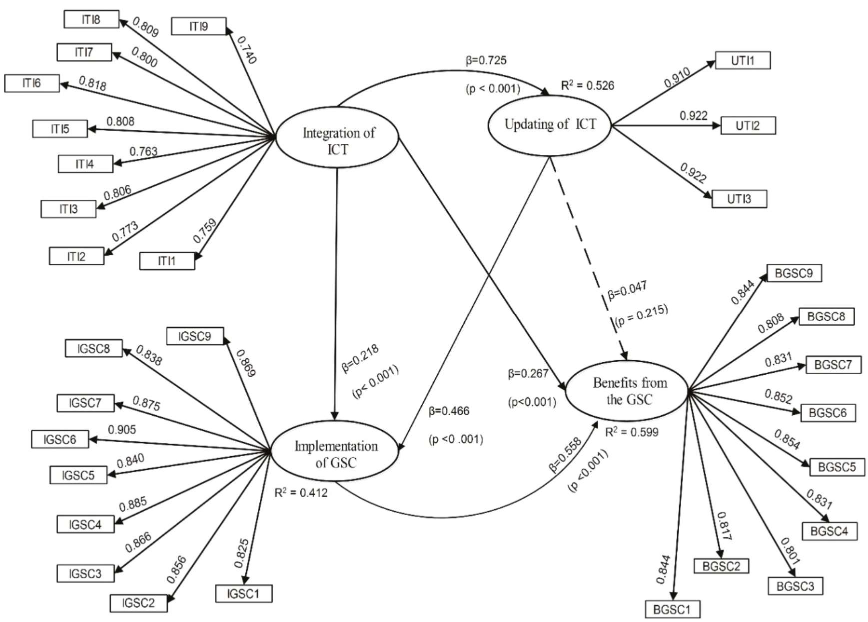

Figure 2. Model developed.

The efficiency indices obtained for the model are as follows and as it can be observed, they all meet the cut-off values established:

- Average path coefficient (APC) = 0.380, $p < 0.001$
- Average R-squared (ARS) = 0.512, $p < 0.001$
- Average adjusted R-squared (AARS) = 0.509, $p < 0.001$
- Average block VIF (AVIF) = 2.110, acceptable if ≤ 5, ideally ≤ 3.3
- Average full collinearity VIF (AFVIF) = 2.438, acceptable if ≤ 5, ideally ≤ 3.3
- Tenenhaus GoF (GoF) = 0.609, small ≥ 0.1, medium ≥ 0.25, large ≥ 0.36

According to values in Figure 2, the structural equations obtained of the model are presented below:

- Updating of ICT = 0.725 Integration of ICT + Error
- Implementation of GCS = 0.218 Integration of ICT + 0.466 Updating of ICT + Error
- Benefits from the GSC = 0.558 Implementation of GSC + 0.267 Integration of ICT + 0.047 Updating of ICT + Error

4.5.1. Direct Effects in the Model

Figure 1 displays the hypothesis considered in the initial model, the direct effects of this are illustrated in Figure 2 and this is used as a basis for the following conclusions:

H_1: There is necessary statistical certainty to say that the *Integration of ICT* has a direct and PE on the *Updating of ICT* within a GSC, since when the first LTV increases its standard deviation by one unit, the second does so by 0.725 units.

H_2: There is necessary statistical certainty to say that the *Integration of ICT* has a direct and PE on the *Implementation of GSC* since when the first LVT increases its standard deviation by one unit, the second does so by 0.218 units.

H_3: There is necessary statistical certainty to say that *Updating of ICT* has a direct and PE on the *Implementation of a GSC* since when the first LTV increases its standard deviation by one unit, the second does so by 0.466 units.

H_4: There is necessary statistical certainty to say that the *Integration of ICT* has a direct and PE when it comes to obtaining the *Benefits from the GSC* with its implementation, since when the first LTV increases its standard deviation by one unit, the second does so by 0.267 units.

H_5: There is not necessary statistical certainty to say that *Updating of* ICT has a direct and PE when it comes to obtaining the *Benefits from the GSC* with its implementation; this is stated with a 95% confidence level, as the associated p-value is greater than 0.05.

H_6: There is necessary statistical certainty to say that the *Implementation of GSC* has a direct and PE when it comes to obtaining the *Benefits from the GSC* with its implementation, since when the first LTV increases its standard deviation by one unit, the second does so by 0.558 units.

It is very significant to note the direct effect the LTV of the *Benefits from the GSC* has and that 59.9% of the time it can be explained by the variables *Integration of ICT*, *Updating of ICT* and *Implementation of GSC*. Its R squared has a value of 0.599, 16.2% of which stems from the variable *Integration of ICT*, 2.7% from the variable *Updating of ICT* and 41% from the LTV *Implementation of a GSC*. Using these findings as our base, we can conclude that organizations must prioritize the successful *implementation of GSC*, since it is what has the greatest impact and explanatory power when it comes to obtaining the *Benefits from the GSC*.

4.5.2. Indirect Effects in the Model

In the model assessed, which is illustrated in Figure 2, can be seen 4 indirect effects, defined as follows:

1. The LTV entitled *Integration of ICT* has an indirect two-segment impact on the LTV entitled *Implementation of GSC*, which is a result of the measurement variable *Updating of ICT*. Whereby, the indirect effect is of 0.338 ($p < 0.001$), which is statistically significant and can explain up to 18.8% of its variability.
2. The LTV entitled *Integration of ICT* has an indirect two-segment impact on the LTV entitled *Benefits from the GSC*, which comes about through the measurement variable *Updating of ICT* and *Implementation of a GSC*. Whereby, the indirect effect is of 0.155 ($p < 0.004$), which is statistically significant and can explain up to 9.4% of its variability.

3. The LTV entitled *Integration of ICT* has an indirect three-segment impact on the LTV entitled *Benefits from the GSC*, which comes about through the measurement variable *Updating of ICT* and measurement variable *Implementation of GSC*. In this case, the indirect effect is of 0.189 ($p < 0.001$), which is statistically significant and can explain up to 11.5% of its variability.
4. The LTV entitled *Updating of ICT* has an indirect two-segment impact on the LTV entitled *Benefits from the GSC*, which comes about through the measurement variable *Implementation of GSC*. Whereby, the indirect effect is of 0.260 ($p < 0.001$), which is statistically significant and can explain up to 15.2% of its variability.

Table 7 shows the sum of the total indirect effects—the sum of the effects of two and three segments which exist between the variables in the projected in Figure 1.

Table 7. Sum of Indirect Effects.

To	From	
	Integration of ICT	**Updating of ICT**
Implementation of GSC	0.338 ($p < 0.001$) ES = 0.188	
Benefits from the GSC	0.334 ($p < 0.001$) ES = 0.209	0.260 ($p < 0.001$) ES = 0.152

4.5.3. Total Effects in the Model

The totality of the indirect and direct effects affords the total effects, which are shown in Table 8. It is noteworthy that in three variables the direct effect is the same as the total effect, which indicates that there is no indirect effect and in the other three the sum of the direct and indirect effects is included. It is vital to note that the direct effect of *Updating of ICT* with the variable *Benefits from the GSC* is only 0.047 and that it was not significant with a 95% confidence level. The indirect effect via the variables of *Updating of ICT* and the variable *Benefits of GSC* is of 0.260; in other words, the indirect effect is much greater and more significant than the direct effect, which shows that a company must make sure they have all the most *updating ICT* equipment. This also becomes an advantage when it comes to the implementation and management of a GSC and are the only way to obtain its benefits.

Table 8. Total Effects.

To	From		
	Integration of ICT	**Updating of ICT**	**Implementation of GSC**
Updating of ICT	0.725 ($p < 0.001$) ES = 0.526		
Implementation of GSC	0.556 ($p < 0.001$) ES = 0.309	0.466 ($p < 0.001$) ES = 0.291	
Benefits from the GSC	0.611 ($p < 0.001$) ES = 0.372	0.307 ($p < 0.001$) ES = 0.179	0.558 ($p < 0.001$) ES = 0.410

5. Conclusions and Limitations

The model proposed and the six hypotheses, were valid with information from the Mexican manufacturing industry but their conclusions can be extended to the rest of this industrial sector in other countries, since in the Mexican manufacturing industry the sector is basically composed of companies from all around the world, such as United States of America, Germany, Japan, France, China and so forth.

Based on the results obtained, it can be observed that the *Integration of ICT* and *Updating of ICT* are related. This is because one complements the other, which is validated via H_1, as the greatest and most significant direct effect in the entire model, since keeping ICTs integrated and updated provides a platform that helps companies to exchange knowledge, align processes and achieve operational flexibility. Furthermore, the integration of ICT affects the efficiency and effectiveness of business processes within and beyond the boundaries of the organization and updated ICTs become an important advantage that is reflected in the efficiency of operations performance [26,56].

Additionally, it is very important to highlight that ICTs constitute an effective tool, which facilitates the *implementation of a GSC*. The above statement is proven through the total and significant effect, which the LTV Integration of ICTs has on the variable Implementation of a GSC. In addition to that, Gunasekaran, et al. [57] mention the importance of involving ICT in the *implementation of GSC*, since this allows the collaboration and exchange of data and information, generating agility in decision making. Besides, Lee, Ooi, Chong and Seow [22] mention that having ICT integrated and updated through a GSC, a series of financial, productive and environmental benefits are created only if the companies see the adoption and implementation of the GSC as an advantage.

Using ICTs of a high technological standard in the implementation and management of a GSC is a strategic priority [26]; these ICTs generate benefits for the supply chain in the long-term. It is important to recognize, however, that those benefits can only be obtained through the Implementation of a successful GSC, as it is the measurement variable in this case. This shows that the ICT is only important when applied to an ecological SC, and, according to Marinagi, et al. [58], the development of current ICT systems for GSC supports and accelerates all commercial activities, improving decision making and productivity, and, according to Marinagi, Trivellas and Sakas [20], can generate a competitive advantage throughout the SC.

The analysis of the relationship between the Implementation of ICTs in the Benefits from the GSC is also important. The direct effect was just 0.267 (see Figure 2) but the indirect effect was of 0.334, achieved through Updating of ICT and the Implementation of the GSC as mediator variables. The above shows the importance of ICTs but only if they are up-to-date and applied to green supply chains, as on their own, the benefits are minimal. In this way, there is a total effect between variables of 0.611, the second greatest observed.

Lastly, it is important to highlight that according to Luthra, Garg and Haleem [32], a GSC generates a series of economic benefits that will be reflected in the reduction of costs of products and processes. For example, social benefits will contribute to the protection of the environment and will create a level of awareness of the clients, which will help to increase the sales and can aid to achieve social performances and competitiveness factors. These benefits help to minimize ecological damage and generate a global economic benefit [59]. This statement is proven by the total and significant effect between the variable Implementation of a GSC and Benefits from the GSC.

The afore-mentioned results indicate that ICT investments must be duly implemented in supply chain and they must be implemented to an adequate technological update which allows for the visibility of the same. In addition, information must be exchanged in real-time (with providers, production system departments and clients) and they must follow all the rules and standards established by the country in which the company is located.

6. Future Studies

The success of a GSC depends on many factors and in this study, we have only considered the integration of ICT and its technological update. In future studies we will try to integrate factors associated to the level of education and training that staff have, as a high level of knowledge is needed in order to use these technologies—to reprogram them for other activities and adapt them to different production lines, as is pointed out by Jabbour and de Sousa Jabbour [59]. It is also intended to use the remaining information from the questionnaire to design more structural equations models and to follow up on this research with the association of other LTVs, such as the ICT flexibility.

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sustainability

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Review

Analysis of Evaluation Methods of Sustainable Supply Chain Management in Production Engineering Journals with High Impact

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Abstract: Nowadays, scholars need to know the trends for specific themes and how the main methods are applied to solve the gaps. The research problem for this work is the assessment of methods used in the sustainable supply chain, published in journals with a high impact factor and especially in the production engineering field. The methodology utilized was an adapted version of the "Methodi Ordinatio", in structured stages to select a limited class of papers of high scientific relevance, to show how the methods are being used. The search steps included the filtering of journals in the research field with relevant impact factors and selecting databases and keywords; reading titles and abstracts; classifying the number of citations; and critical reading of all papers listed in the bibliographic portfolio. The research results and analysis of frequency of papers in the portfolio were used to identify and describe the most commonly used evaluation methods, the correlated theories, advantages, and disadvantages of each researched work.

Keywords: sustainable supply chain management; research methods; scientific production; metrics; indicators

1. Introduction

According to Bai and Sarkis [1], environmental concerns of consumers, companies, and governments have increased in recent years. Sustainable supply chain management enables companies to increase their cost efficiency and improve productivity and product quality, resulting in competitive advantage [2].

The evaluation methods used to measure the performance of sustainable supply chains help organizations choose the best investments in programs and initiatives to generate the best return and support the development of environmentally responsible suppliers [1]. To accompany this trend, the availability of scientific works on this subject in databases is steadily growing. However, researchers are currently struggling to select papers considered prestigious and renowned by the scientific community [3]. A simple search of scientific papers to create a literary base for research without a well-structured process merely creates a vague stage that lacks scientific effectiveness.

The increasing of journals and publications about methods applied in several contexts, generates a necessity to study how these methods are really being developed and used in specific fields, so as to balance the principles of the triple bottom line (social, environmental and financial) [1,3].

There is a great number of works in traditional bibliographic research. However, in order to know current trends in a theme, the present methodologies do not have accessible tools for performing a more specific analysis.

This study focuses on an adapted methodology to search the main methods published in journals from the production engineering field [4]. This covers a large number of themes such as public administration and business, accounting and tourism, as well as production engineering. Thus, by the increased number of journals existing in this field of interest, the purpose of this study is to analyze the sustainable supply chain management evaluation models currently used in the literature, by applying a structured methodology capable of selecting specific and relevant scientific articles to answer questions in the production engineering field.

The relevance of this development is the generation of a capacity to concentrate efforts in the investigation of specific points to answer questions about only one field of interest, and not an extensive literature review that covers other irrelevant material.

Some literature review studies have already studied the topic of supply chain management and its applications, each with its own specific characteristics, but none have yet addressed the theme of sustainable supply chain management in specific production engineering journals. Kouvelis et al. [5] for example conducted a literature review focused on supply chain management that was published in a journal of production and operations management (POM). As a result, the articles found addressed topics such as supply chain design, uncertainty and whip effect, supply chain contracts, decisions on capacity and supply, applications and practices, and supply chain management education. Zimmer et al. [6] reviewed the sustainable supplier management (SSM) literature, focusing on decision-making support models in the selection, monitoring and development of sustainable suppliers. The justification for this study lies in the assumption that environmental management indicators can be the most important performance evaluation methods for companies to increase their competitive advantage in the near future [2].

Moreover, studies on evaluation methods that support the environmental management of the company and the development of suppliers are still limited in the literature [1,7]. The theoretical discussion of this study is based on the relevance of analyses, by bringing a discussion on methods applied in production engineering, which grows exponentially. The articles produced in the theme of sustainable supply chain management, in general, are quite broad and so researchers need to treat and filter the results that interest them. Therefore, this article seeks to overcome this difficulty, motivating a debate more directed to the scholars of this specific field.

Consequently, the methods that make it possible to evaluate sustainable supply chain management in high impact factor journals can benefit stakeholders, both in companies and universities, and serve as a reference for future research. Thus, the question that this study examines is: Which models for assessing sustainable supply chain management are being used in papers published in journals with a high impact factor?

2. Materials and Methods

To create a bibliographic portfolio, 12 stages were adopted as follows:

In the first stage, the filtering of periodicals for the interested field was performed (in this case, production engineering). The second stage checked the impact factor score (IF) of the journals and sorted them in descending order. The IF is calculated annually by the Institute for Scientific Information for the journals in its database, and published by the Journal Citations Reports (JCR) [8]. The journals with an IF value under 1 were excluded since they represent journals with a low IF to the field. Three journals with this characteristic were excluded, resulting in 154 journals.

In the third stage, another filtering of journals took place, focused on production engineering. In our application from 154 journals in the production engineering category (with an IF greater than 1), 115 were found aligned with this theme. For filtering, each of the 154 journals were searched in the databases that describe the journals and their scientific indicators [9,10].

The fourth stage addresses the selection of databases to conduct the search for articles. Given our familiarity with tools created in previous studies, we worked with the databases Scopus and Science Direct in the practice stage of this work. However, there is a wide range of databases available, such as Science Direct, Scientific Electronic Library Online (SciELO.), Scopus, and Web of Science ISI (Institute for Scientific Information) [3,11,12].

The fifth stage consists of keyword selection that will guide the search. It should be noted that the keywords in scientific papers are used for the indexes and search engines to find relevant documents and, thus, provide a description of the subjects in discussion [13]. Seven keywords were selected for the "indicators" (assessment, evaluation, measurement, performance indicators, measures, metrics), two for "supply chain" (supply chain, supplier), and four for "sustainable" (green, sustainability, sustainable, triple bottom line). Figure 1 shows a diagram with the bibliographic research methodology structure.

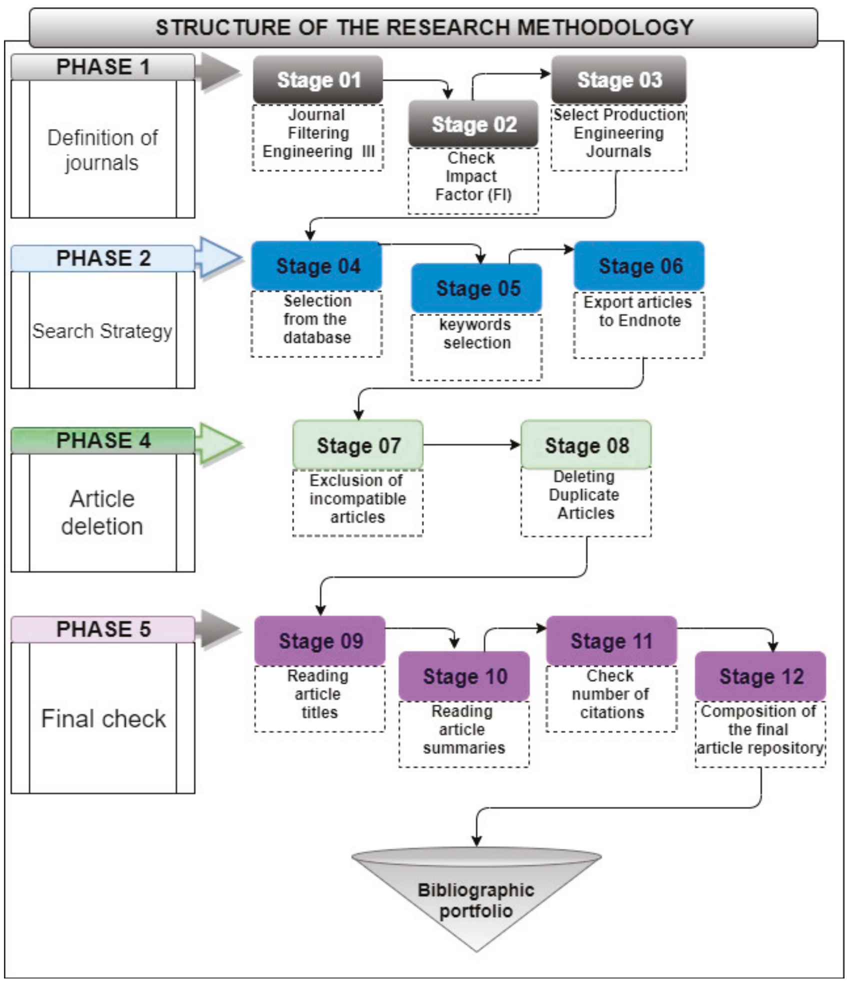

Figure 1. Structure of the methodology.

The main search filters used in the databases were: (a) the Boolean word "AND", used between the keywords to filter papers with the three combinations of keywords in at least one of the fields of title, abstract, and keyword; (b) the keywords were searched in English to ensure searches in international journals; (c) the search period was defined as 2010 to 2019 to guarantee the inclusion of non-obsolete materials [3]; and, (d) in terms of file type, only "papers" were included to select specific documents for researchers. The search generated 56 keyword combinations. These combinations led to 35,842 papers, of which 6760 were found in the Scopus database and 29,082 in the Science Direct database.

The sixth stage consisted of exporting papers to Endnote in order to manage the gross bibliographic references. The seventh stage was defined to exclude papers that did not belong to the journals selected in stage three. This stage led to the elimination of 32,485 papers, since they did not belong to any of the 115 journals in the production engineering theme.

In the eighth stage, the exclusion of duplicate papers was performed. Of the 3357 papers, 2838 were duplicates and therefore were excluded from the research database. The remaining non-duplicated papers totaled 519 in the database for analysis. The ninth stage consisted of reading titles of the papers to see if they were associated with the objective of the research. After reading the papers, 147 titles were deleted because the title was not related to the research subject. The remaining papers totaled 372 for summary analysis.

This stage introduces a subjective aspect of research; however, as recommended by Tranfield, et al., [14] this stage should be carried out by more than one reviewer to minimize the subjectivity of the research.

Stage ten is organized in two steps. This stage consisted of reading the abstracts to check the consistency with the purpose of research. Of the 372 papers, 183 had abstracts that did not match the subject of research and were excluded. The abstracts of 189 papers were consistent with the research subject and were maintained in the database.

Stage eleven consisted of verifying the number of citations of each of the 189 papers in Google Scholar database. These papers were classified according to the decreasing number of citations. The cutoff point of the most cited and least cited articles was based on the Pareto's rule (80/20) considering that approximately 20% of the most cited articles represents 80% of the total citations, totaling 14 articles. The 14 most cited articles were part of Repository A, while the 175 least cited papers were subjected to a differentiated analysis. It was found that the authors of the 175 least cited papers were part of the 14 most cited papers. Thus, 29 of the least cited papers had authors who were among the most cited, and were therefore reclassified to Repository B. The remaining 146 were eliminated from the study because they did not meet the proposed requirements.

Stage twelve consisted of adding the papers of repositories A and B to Repository C (with 43 papers). These 43 papers had high impact factor on sustainable supply chain and applied to production engineering. The papers are listed in alphabetical order in Box 1.

Box 1. Bibliographic portfolio of papers with high impact factor about the sustainable supply chain applied to Production Engineering.

1. AZEVEDO, S. G.; CARVALHO, H.; MACHADO, V. C. The influence of green practices on supply chain performance: a case study approach. Transportation research part E: logistics and transportation review, v. 47, n. 6, p. 850-871, 2011. [15]
2. BAI, C.; DHAVALE, D.; SARKIS, J. Complex investment decisions using rough set and fuzzy c-means: An example of investment in green supply chains. European Journal of Operational Research, v. 248, n. 2, p. 507-521, 2016. [16]
3. BAI, C.; SARKIS, J. Green supplier development: analytical evaluation using rough set theory. Journal of Cleaner Production, v. 18, n. 12, p. 1200-1210, 2010. [1]
4. CHIOU, T.; CHAN, H. K.; LETTICE, F.; CHUNG, S. H. The influence of greening the suppliers and green innovation on environmental performance and competitive advantage in Taiwan. Transportation Research Part E: Logistics and Transportation Review, v. 47, n. 6, p. 822-836, 2011. [2]
5. DENG, H.; LUO, F.; WIBOWO, S. Multi-Criteria Group Decision Making for Green Supply Chain Management under Uncertainty. Sustainability, v. 10, p. 3150-3163, 2018. [17]

Box 1. *Cont.*

6. GOVINDAN, K.; KHODAVERDI, R.; JAFARIAN, A. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. Journal of Cleaner Production, v. 47, p. 345-354, 2013. [18]
7. GREEN JR, K. W.; ZELBST, P. J.; MEACHAM, J.; BHADAURIA, V. S. Green supply chain management practices: impact on performance. Supply Chain Management: An International Journal, v. 17, n. 3, p. 290-305, 2012. [19]
8. HSU, C.; KUO, T.; CHEN, S.; HU, A. H. Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. Journal of Cleaner Production, v. 56, p. 164-172, 2013. [20]
9. KUO, R. J.; WANG, Y. C.; TIEN, F. C. Integration of artificial neural network and MADA methods for green supplier selection. Journal of Cleaner Production, v. 18, n. 12, p. 1161-1170, 2010. [21]
10. KUSI-SARPONG, S.; GUPTA, H.; SARKIS, J. A supply chain sustainability innovation framework and evaluation methodology. International Journal of Production Research, v. 57, n. 7, p. 1990-2008, 2019. [22]
11. LIN, R. Using fuzzy DEMATEL to evaluate the green supply chain management practices. Journal of Cleaner Production, v. 40, p. 32-39, 2013. [23]
12. LIN, Y.; TSENG, M. Assessing the competitive priorities within sustainable supply chain management under uncertainty. Journal of Cleaner Production, v. 112, p. 2133-2144, 2016. [24]
13. LOZANO, R.; HUISINGH, D. Inter-linking issues and dimensions in sustainability reporting. Journal of Cleaner Production, v. 19, n. 2, p. 99-107, 2011. [25]
14. LUTHRA, S.; MANGLA, S. K.; XU, L.; DIABAT, A. Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain. International Journal of Production Economics, v. 181, p. 342-349, 2016. [26]
15. MANGLA, S. K.; GOVINDAN, K.; LUTHRA, S. Critical success factors for reverse logistics in Indian industries: a structural model. Journal of Cleaner Production, v. 129, p. 608-621, 2016. [27]
16. PATCHARA, P.; CHUNQIAO, T. An integrated multi-criteria decision-making model based on prospect theory for green supplier selection under uncertain environment: A case study of the Thailand palm oil products industry. Sustainability, v. 11, p.1871-1894, 2019. [28]
17. TSENG, M.; CHIU, A. Evaluating firm's green supply chain management in linguistic preferences. Journal of cleaner production, v. 40, p. 22-31, 2013. [29]
18. TSENG, M. L.; LIMB, M. K.; WONG, W. P.; CHEN, Y. C.; ZHAN, Y. A framework for evaluating the performance of sustainable service supply chain management under uncertainty. International Journal of Production Economics, v. 195, p. 359-372, 2018. [30]
19. PATHAK, D. K.; THAKUR, L. S.; RAHMAN, S. Performance evaluation framework for sustainable freight transportation systems, International Journal of Production Research, v. 57, n. 19, p. 6202-6222, 2019. [31]
20. CHOI, S. B.; MIN, H.; JOO, H. Y.; CHOI, H. B. Assessing the impact of green supply chain practices on firm performance in the Korean manufacturing industry, International Journal of Logistics Research and Applications, v. 20, n. 2, p. 129-145, 2016. [32]
21. SHAFIQ, A.; JOHNSON, P.; KLASSEN, R.; AWAYSHEH, A. Exploring the implications of supply risk on sustainability performance, International Journal of Operations & Production Management, v. 37 N. 10, p. 1386-1407 2017. [33]
22. GANDHI, S.; MANGLA, S. K.; KUMAR, P.; KUMAR, D. A combined approach using AHP and DEMATEL for evaluating success factors in implementation of green supply chain management in Indian manufacturing industries, International Journal of Logistics Research and Applications, v. 19, n. 6, p. 537-561, 2016. [34]
23. LUN, Y. H. V. Green management practices and firm performance: A case of container terminal operations, Resources, Conservation and Recycling, v. 55, n. 6, p. 559-566, 2011. [35]
24. SHENC, L.; OLFAT, L.; GOVINDANB, K.; KHODAVERDIA, R. DIABAT, A. A fuzzy multi criteria approach for evaluating green supplier's performance in green supply chain with linguistic preferences, Resources, Conservation and Recycling, v. 74, p. 170 – 179, 2013. [36]
25. KIM, J.-S.; SHIN, N. The Impact of Blockchain Technology Application on Supply Chain Partnership and Performance. Sustainability, v. 11, n 21, p. 6181, 2019. [37]
26. SUBIC, A.; SHABANI, B.; HEDAYATI, M.; CROSSIN, E. Performance Analysis of the Capability Assessment Tool for Sustainable Manufacturing. Sustainability, v. 5, n. 8, p. 3543-3561, 2013. [38]
27. BARATA, J. F. F.; QUELHAS, O. L. G.; COSTA, H. G.; GUTIERREZ, R. H.; DE JESUS LAMEIRA, V.; MEIRIÑO, M. J. Multi-Criteria Indicator for Sustainability Rating in Suppliers of the Oil and Gas Industries in Brazil. Sustainability, v. 6, n. 3, p. 1107-1128, 2014. [39]
28. VALIDI, S., BHATTACHARYA, A.; BYRNE, P. A Case Analysis of a Sustainable Food Supply Chain Distribution System - A Multi-Objective Approach. International Journal Of Production Economics, v. 152, p. 71-87, 2014. [40]

Box 1. *Cont.*

29. HAYAMI, H.; NAKAMURA, M.; NAKAMURA, A. O. Economic performance and supply chains: The impact of upstream firms' waste output on downstream firms' performance in Japan, International Journal of Production Economics, v. 160, p. 47-65, 2015. [41]
30. ESFAHBODI, A.; ZHANG, Y.; WATSON, G. Sustainable supply chain management in emerging economies: Trade-offs between environmental and cost performance', International Journal of Production Economics, v. 181, p. 350-366, 2016. [42]
31. KATIYAR, R.; MEENA, P. L.; BARUA, M.; TIBREWALA, R.; KUMAR, G. Impact of sustainability and manufacturing practices on supply chain performance: Findings from an emerging economy, International Journal of Production Economics, v. 197, p. 303-316, 2018. [43]
32. WANG, X.; CHAN, H. K. A hierarchical fuzzy TOPSIS approach to assess improvement areas when implementing green supply chain initiatives, International Journal of Production Research, v. 51, n. 10, p. 3117-3130, 2013. [44]
33. LI, C. An integrated approach to evaluating the production system in closed-loop supply chains, International Journal of Production Research, v. 51, n. 13, p. 4045-4069, 2013. [45]
34. TSUI, C, W.; TZENG, G. H.; WEN, U. P. A hybrid MCDM approach for improving the performance of green suppliers in the TFT-LCD industry, International Journal of Production Research, v. 53, n. 21, p. 6436-6454, 2014. [46]
35. GOSWAMI, M.; GHADGE. A. A supplier performance evaluation framework using single and bi-objective DEA efficiency modelling approach: individual and cross-efficiency perspective, International Journal of Production Research, p. 1-24, 2019. [47]
36. FENG, M.; YU, W.; WANG, W.; WONG, C. Y.; XU, M.; XIAO, Z. Green supply chain management and financial performance: The mediating roles of operational and environmental performance, Business Strategy and the Environment, v. 27, n. 7, p. 811-824, 2018. [48]
37. BLASS, V.; CORBETT, C. J. Same Supply Chain, Different Models Integrating Perspectives from Life Cycle Assessment and Supply Chain Management, Journal of Industrial Ecology, v. 22, n. 1, p. 18-30, 2018. [49]
38. BAG, S. Green strategy, supplier relationship building and supply chain performance: total interpretive structural modelling approach. International Journal of Procurement Management, v. 9, n. 4, p. 398-426, 2016. [50]
39. ARAMPANTZI, C.; MINIS, I. A new model for designing sustainable supply chain networks and its application to a global manufacturer. Journal of Cleaner Production, v. 156, p. 276-292, 2017. [51]
40. NOYA, I.; VASILAKI, V.; STOJCESKA, V.; GONZÁLEZ-GARCÍA, S.; KLEYNHANS, C.; TASSOU, S.; MOREIRA, M. T.; KATSOU, E. An environmental evaluation of food supply chain using life cycle assessment: a case study on gluten free biscuit products, Journal of Cleaner Production, v. 170, p. 451-461, 2017. [52]
41. CHATTERJEE, K.; PAMUCAR, D.; ZAVADSKAS, E. K. Evaluating the performance of suppliers based on using the R'AMATEL-MAIRCA method for green supply chain implementation in electronics industry, Journal of Cleaner Production, v. 184, p. 101-129, 2018. [53]
42. DAS, D. The impact of Sustainable Supply Chain Management practices on firm performance: Lessons from Indian organizations, Journal of Cleaner Production, v. 203, p. 179-196, 2018. [54]
43. KHAN, S.A; KUSI-SARPONG, S.; KOW ARHIN, F.; KUSI-SARPONG, H. Supplier sustainability performance evaluation and selection: A framework and methodology, Journal of Cleaner Production, v. 205, p. 964-979, 2018. [55]

In sequence, the bibliometric and systematic analysis of the 43 papers were performed.

3. Results

3.1. Bibliometric Analysis

3.1.1. Scientific Recognition of Articles

In order to verify the scientific recognition of the articles belonging to the bibliographic portfolio, a search was carried out to verify the number of citations of each article [56]. The data were sorted according to the decreasing number of citations. Table 1 shows the results of the citations of the 43 articles that comprise the bibliographic portfolio. It should be noted that the most recent articles have a low number of citations in comparison to the older ones, as they have had less time to be cited [3].

Table 1. Scientific relevance of articles.

Paper	Year	N° Citations	% of Citations
Green Jr et al. [17]	2012	656	10.81
Govindan et al. [16]	2013	549	9.04
Chiou et al. [2]	2011	504	8.30
Kuo et al. [19]	2010	477	7.86
Bai Sarkis [1]	2010	436	7.18
Azevedo et al. [13]	2011	431	7.10
Lozano Huisingh [22]	2011	430	7.08
Hsu et al. [18]	2013	380	6.26
Lin [20]	2013	352	5.80
Shen et al. [36]	2013	319	5.25
Tseng Chiu [25]	2013	276	4.55
Validi et al. [40]	2014	181	2.98
Lun [35]	2011	137	2.26
Wang Chan [44]	2013	105	1.73
Luthra et al. [26]	2016	77	1.27
Bai et al. [14]	2016	76	1.25
Lin Tseng [21]	2016	75	1.24
Chatterjee et al. [53]	2018	71	1.17
Gandhi et al. [34]	2016	60	0.99
Mangla et al. [23]	2016	58	0.96
Tsui et al. [46]	2014	46	0.76
Tseng et al. [30]	2018	38	0.63
Arampantzi minis [51]	2017	37	0.61
Li [45]	2013	31	0.51
Bag [50]	2016	29	0.48
Kusi-Sarpong et al. [22]	2019	26	0.43
Katiyar et al. [43]	2019	24	0.40
Feng et al. [48]	2018	23	0.38
Hayami et al. [41]	2015	22	0.36
Blass Corbett [49]	2018	20	0.33
Choi et al. [32]	2016	19	0.31
Barata et al. [39]	2014	19	0.31
Shafiq et al. [33]	2017	18	0.30
Kan et al. [55]	2018	18	0.30
Noya et al. [52]	2017	16	0.26
Das [54]	2018	13	0.21
Subic et al. [38]	2013	12	0.20
Deng et al. [17]	2018	3	0.05
Pathak et al. [31]	2019	3	0.05
Patchara Chunqiao [24]	2019	1	0.02
Kin Shin [37]	2019	1	0.02
Esfahbodi et al. [42]	2016	1	0.02
Goswami Ghadge [47]	2019	1	0.02
Lozano Huisingh [22]	2011	431	7.10

Table 1 shows the number of article citations collected from the Google Scholar database [57]. In addition, it should be noted that the 6 articles with a greater number of citations represent 50.29% of the total citations. Two articles with the lowest number of citations that belong to Repository B are redundant articles, but nonetheless, closely aligned with the research objective.

3.1.2. Relevance of Journals

Figure 2 shows the relevance of periodicals present in the portfolio. This analysis seeks to verify which journals publish the most on the sustainable supply chain subject, according to the delimitations of the research.

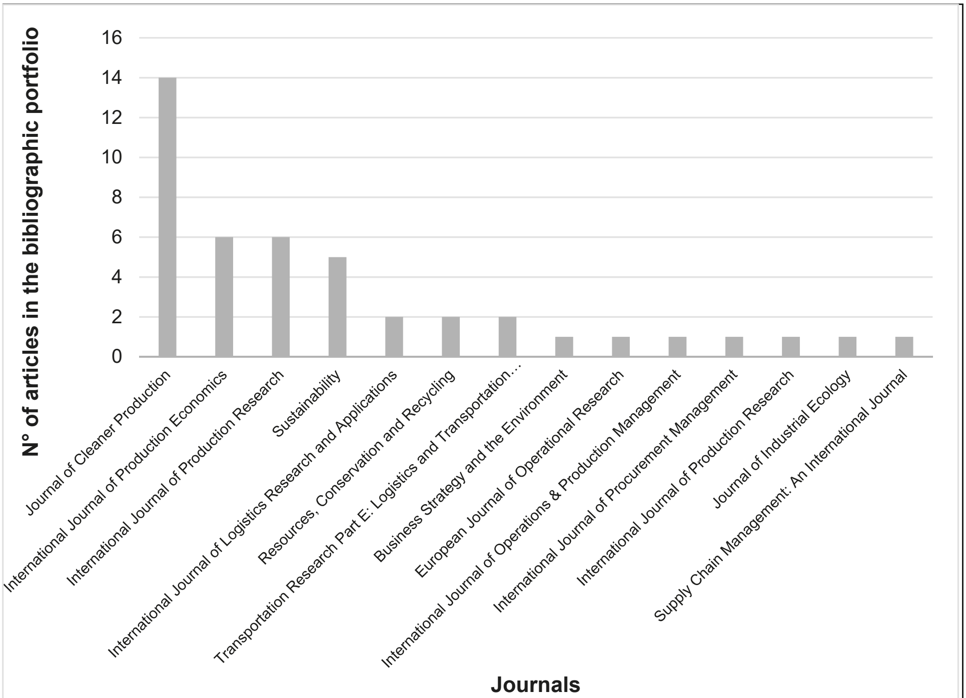

Figure 2. Relevance of journals in the bibliographic portfolio.

According to Figure 2, the journal that most published articles on sustainable supply chain in the field of production engineering was the Journal of Cleaner Production, with 14 articles, corresponding to a 32.55% of the portfolio. The International Journal of Production Economics and International Journal of Production Research, each have 6 articles, representing 13.95% of the total articles in the bibliographic portfolio, while Sustainability has 5 articles, representing 11.62% of the total articles. The International Journal of Logistics Research and Applications, Resources, Conservation and Recycling and Transportation Research Part E: Logistics and Transportation Review, each have 2 articles, representing 11.62% of the total number of articles. The other journals have only one article in the bibliographic portfolio. It is important to highlight the relevance of the Journal of Cleaner Production to the bibliographic portfolio, as it represents 32.44% of the total articles and 48.17% of citations.

3.1.3. Relevance of Authors

As shown in Figure 3, one author has four articles, as the main author or co-authored with others, three authors have three articles, five authors have two articles in the bibliographic portfolio in authorship or co-authorship and the other authors have just one article. For the analysis under consideration, this may also be an indication that the sustainable supply chain issue is of interest to various universities and researchers.

This analysis demonstrates that there is a plurality of researchers on this topic. Therefore, this scope of research may demonstrate that the topic is still under development in the research universe and that there are still gaps to fill.

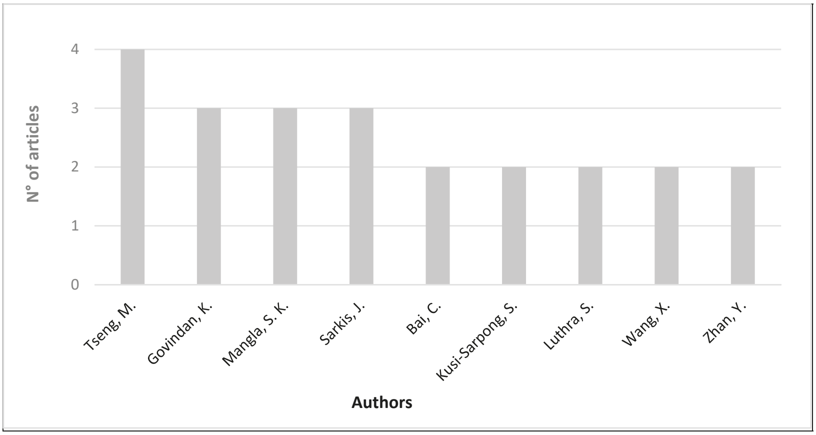

Figure 3. Representativeness of the authors of the bibliographic portfolio.

3.1.4. Publications for Years

Figure 4 shows the number of publications for each of the 10 years surveyed. It should be noted that the year 2019 is also included in the research, although only until October, when the data collection for the bibliographic portfolio were finalized.

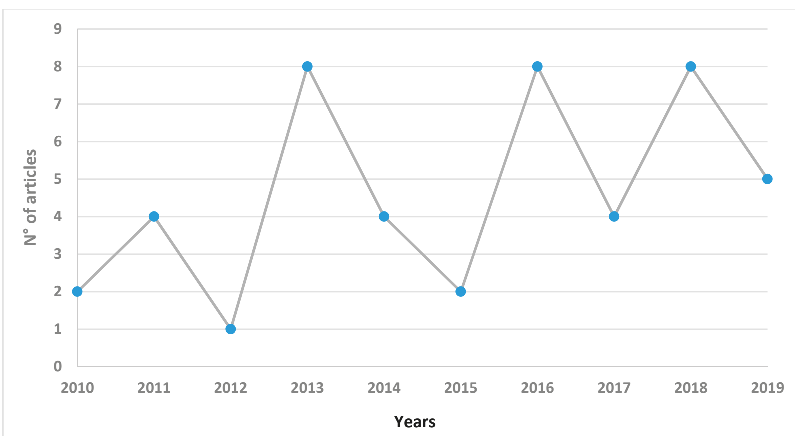

Figure 4. Publications by years of bibliographic portfolio.

According to the analysis performed, and shown in Figure 4, every year surveyed added articles to the bibliographic portfolio. The years 2013, 2016 and 2018 have the largest number of articles published in the bibliographic portfolio, with 8 articles each year, representing 18.60% of the total articles each year.

The year 2019, even though it is not being considered in its entirety, has 5 articles, demonstrating that this year may surpass the others, while the years 2011, 2014 and 2017 have four publications, representing 9.30% each year, respectively.

The fourth largest number of publications is concentrated in 2010 and 2015, with two publications each year, and 2012 has only one publication, the lowest number found.

This analysis shows a growing trend of research development in this thematic area, because, with a small variability, the number of publications increases over the last years researched [35]. From 2016, the number of publications in the bibliographic portfolio remained high, ranging from 4 to 8 publications.

3.2. Systemic Analysis

After reading the 189 papers categorized in stage eleven, we selected 43 articles to create the final bibliographic portfolio, listed in stage twelve, for full reading and analysis, due to their greater relevance and impact in the area of research.

As shown in Table 1, the following methods for evaluating the sustainable supply chain were identified in the papers: rough set theory; data envelopment analysis (DEA) combined with the analytic network process (ANP), artificial neural network (ANN) and multi-attribute decision analysis (MADA); structural equation modeling; grounded theory; exploratory case study; decision-making trial and evaluation laboratory (DEMATEL); fuzzy multi-criteria; fuzzy multi-criteria combined with technique for order of preference by similarity to ideal solution (TOPSIS); fuzzy multi-criteria combined with DEMATEL; fuzzy multi-criteria + ANP, BW-MCDM, AHP, multivariate statistics, sustainable production capability assessment tool (CMAT), Tism + Fahp, blockchain technology (BCT), cluster analysis + one way ANOVA, ELECTRE TRI, PROMETHEE, AHP+TOPSIS and, finally, the analytic hierarchy process (AHP) combined with DEMATEL.

Table 2 shows that the ten first methods with 32 occurrences represent 74.41% of the total of occurrences. These ten main methods found used in the developed models were: fuzzy model (six occurrences); multivariate statistics (six occurrences); exploratory case study (five occurrences); AHP combined with DEMATEL (three occurrences); DEA combined with ANP, RNA and MADA (two occurrences); fuzzy multi-criteria + DEMATEL (two occurrences); fuzzy multi-criteria combined with TOPSIS (two occurrences); structural equation modeling (two occurrences); sustainable manufacturing capacity assessment tool (CMAT) (two occurrences) and TISM + FAHP (two occurrences). In the remaining studies (11 studies), evaluation methods appear only once, as follows: block chain technology (BCT) [37]; cluster analysis + one way ANOVA [32]; ELECTRE TRI [39]; PROMETHEE [46]; DEMATEL [58]; AHP [26]; BW-MCDM [22]; fuzzy multi-criteria + ANP [30]; rough set theory [1]; grounded theory [25] and AHP + TOPSIS [40].

Table 2. Evaluation methods used in the papers of the bibliographic portfolio.

Evaluation Method	No. of Papers	%
Fuzzy Multi-Criteria	6	13.95%
Multivariate Statistics	6	13.95%
Exploratory Case Study	5	11.63%
AHP + DEMATEL	3	6.98%
DEA combined with ANP, RNA, and MADA	2	4.65%
Fuzzy Multi-Criteria + DEMATEL	2	4.65%
Fuzzy Multi-Criteria + TOPSIS	2	4.65%
Structural Equation Modelling	2	4.65%
Sust. Manuf. Capability Assessment Tool (CMAT)	2	4.65%
TISM + FAHP	2	4.65%
AHP	1	2.33%
Blockchain Technology (BCT)	1	2.33%
BW-MCDM	1	2.33%
Cluster Analysis + One Way ANOVA	1	2.33%
DEMATEL	1	2.33%
ELECTRE TRI	1	2.33%
Fuzzy Multi-Criteria + ANP	1	2.33%
Grounded Theory	1	2.33%
PROMETHEE	1	2.33%
Rough Set Theory	1	2.33%
AHP + TOPSIS	1	2.33%
Total	**43**	**100%**

4. Discussion

In this section we analyze the models/methods/methodologies found in the articles listed in the bibliographic portfolio. The evaluation methodologies are discussed, as well as advantages and disadvantages, exploring the trends and possible deficiencies of the application and integration of these methods.

4.1. Fuzzy Multi-Criteria

A fuzzy number transforms a linguistic variable into a real number between 0 and 1, unlike the Boolean theory, which only considers the exact values 0 and 1. Thus, a variable can be partially true or false, thereby creating degrees of relevance between the variables of a study [16,17,24,29,36,55].

The advantage of the fuzzy theory is that it can be applied in many different scenarios and using several possible criteria. However, a fuzzy number depends strongly on the judgment of each decision-maker, which carries a more subjective aspect into the study [16]. In some cases it can lose some refined and important information in precise scales, for example. Thus, some studies might be failing in performing a coherent application of this theory [16–18,23,24,29]. The fuzzy theory must be used in cases wherein the decision-maker is not certain about preferences or might be confused with the possible admitted variations by the nature of the problem itself. When it is not observed systematically, the application could present questionable results.

4.2. Multivariate Statistics

Multivariate statistics analyzes a group of variables together. The main advantage of this method is the considerable number of analyses for variables that represent the problem in question. With this, it is possible to provide a series of interpretations and interaction possibilities to the specialists, since these multivariate statistical methods make it possible to analyze the same phenomenon from different angles and to evaluate the chain of analysis [33,42,52].

One of the disadvantages of multivariate statistics for assessing sustainable supply chain performance is that it uses a large number of variables to solve one unique problem, because it is not enough to know isolated statistical data. Rather, it is important to understand all the information and the relationships present among them [45,54]. Because it is a purely mathematical method, the information extracted from the analysis needs to be validated by experts in the field of study, thus demonstrating vulnerability in this analysis model. These disadvantages make the interpretation of the phenomenon difficult using the chosen variables. On the other hand, in the case that it is organized in a systematic way, this method then brings important information to the decision-maker about the studied problem or necessity. Multivariate statistics analyses provide an understanding of the phenomena in a statistical way, considering multiple variables in the analysis. This technique, correctly integrated with other multi-criteria methods, can help to obtain more efficient results.

4.3. Exploratory Case Study

This method is used at the beginning of a study when the data that must be tested to form the theory are not accurately known. The researcher must define the research problem and the hypotheses to be tested, and go into the field [15,28,35,43,48].

The advantage is that it can initially be applied in any study. The downside of the theory is the impossibility of inferring results to be generalized for other scenarios. The study must be specific to the scenario in which it is applied. In the case of where a case study is conducted to study a success case (TPM—total productive maintenance theory from Toyota, for example) it contributes an interesting learning opportunity for the industries, in order to adapt the formed theory and the best practices found in the case study.

4.4. AHP Combined with DEMATEL

The AHP method is used to establish the priorities of the critical success factors of enterprises. The DEMATEL approach categorizes the causal relationships between these factors [27,34,53]. The advantage is that it is easy to apply and review, and can be applied to qualitative and quantitative variables. The downside is that the results cannot be used in other scenarios. The study must be specific for the scenario in which it was applied.

However, the use of similar multi-criteria methods, such as AHP and DEMATEL, may present deficiencies in the reliability and validity of the constructs used for the study. The problems arising from the misapplication of these methods reveal the tendency of the use of human factor preferences for decision making, which is the opinion of decision makers [56]. The AHP, for example, uses averages in its formulations. This could be a problem for data with great variation.

4.5. DEA Combined with ANP, RNA, and MADA

In the works found, this methodology was used for determining the indicators of green supplier selection, predict the performance measurement values of each indicator, and determine the weight of indicators. After obtaining the performance values for each supplier, the next stage is to conduct a data envelopment analysis to make a final assessment of the suppliers [21,47].

The advantages of this integration are that the data generate better results by evaluating the performance of suppliers. Moreover, the number of efficient suppliers is much lower than if the techniques had been applied to the best suppliers with this methodology. As for the disadvantages, after conducting the study with the suppliers, these suppliers should be classified, since the theory does not perform this task.

4.6. Fuzzy Multi-Criteria Combined with DEMATEL

The linguistic variables are translated into numbers using the fuzzy technique, followed by an analysis of the criteria of cause and effect between the variables found in the study [23,55]. The advantage is that this methodology does not require many variables for its application. The main disadvantage is that the results cannot be replicated in other studies since each model is specific for each company. The particularities of the fuzzy theory mean that it is completely dependent on the opinions of decision-makers.

4.7. Fuzzy Multi-Criteria Combined with TOPSIS

Triangular fuzzy numbers are used to express linguistic values of the subjective preferences of reviewers. These values are transformed into quantifiable numbers, after which the TOPSIS technique is proposed to find the ranking of suppliers [18,44].

The advantages of the theory are that it allows for the assessment of an unlimited range of criteria and performance attributes. Moreover, when the qualitative data are transformed into numbers, they are more easily understood and analyzed. The disadvantage of this theory is that the availability of data is critical to implement the model, and data are not always available to operationalize the study. Also the TOPSIS method presents some problems related to the reversion of ranking, which is also present in the major part of multi-criteria methods, but in the original version of TOPSIS it is more evident. There are efforts and variations of the TOPSIS method trying to minimize this problem.

4.8. Structural Equation Modelling (SEM)

This method is used to study the correlation between variables. It focuses on quantifying how quantifiable variables reflect the unobserved variables (constructs) [2,19]. The advantages of this theory include practices used by businesses to develop their sustainable supply chain to enhance environmental performance of the focal firm (measurable variable) and, consequently, improve organizational performance (construct). It also demonstrates advantage in the exploration of a statistical technique that brings reliability to the results, through the study of the correlation among variables.

One of the disadvantages of the theory is that the model can vary significantly with every company. There is no way of inferring whether the observable variables in an enterprise will generate the same constructs in another corporation, because each organization is unique.

4.9. Sustainable Manufacturing Capacity Assessment Tool (CMAT)

This method uses questionnaires for data collection, using the Likert scale to quantify qualitative data, and later uses statistical analysis for information processing. As advantages, this method presents an analysis of 170 resources linked to the supply chain, and can segment them to gain greater understanding of the demands of the researched environment [38]. The use of expert managers to answer the data collection questionnaire enables a deeper discussion of the critical elements belonging to the supply chain of the studied environment. Moreover, the method makes it possible to carry out a complete evaluation and subsequently propose continuous improvement initiatives through the proposed stages: measure, compare, relate, classify, document and propose improvements [51].

Disadvantages include the limitation of the method in analyzing the other aspects of the triple bottom line, as the method is designed to recognize only environmental aspects linked to the sustainable supply chain, showing difficulties in recognizing social and economic aspects. In addition, the questionnaires must be systematically constructed in order to collect the real information about the problem. It can be a problem if it is not made appropriately. However, this method can undergo adaptations and improvements to meet other aspects not recognized by the original model, which is the case for economic and social aspects.

4.10. TISM + FAHP

The advantages declared by the authors in the literature about the integration of the FAHP (fuzzy analytical hierarchy process) technique with TISM (total interpretive structural modeling) techniques can be defined by providing more sensitive results than using one of the techniques individually [31,50]. Another factor reported is that the integration of these methods makes it possible to perform an assessment with qualitative aspects, using TISM, and quantitative aspects from a nine-point numerical scale (Saaty Scale), using the FAHP method. The TISM method facilitates the transformation of inaccurate and limited articulated data from a complex system into a simple and well-defined model. This method assists in providing interpretation in a structural model [31]. These integrated methods are agile for data execution and processing. Conversely, the integration of these methods generates disadvantages and wrong applications. All TISM methodology has limitations, since it uses purely the expert opinion, which is qualitative in nature [50]. To minimize limitations, integration with another technique can be performed for statistical validation as well as for introducing other variables to the problem.

In this sense, studies [59,60] proposed to solve two research gaps (institutional barriers and resource constraints), combining TISM with SEM (Structural Equation Modeling) and MICMAC analysis. The TISM method uses the opinion of expert groups to understand the relationships between the studied variables and the SEM method with the aid of PLS (partial least squares method) which allows for the evaluation of exogenous variables. The results showed that the use of TISM associated with other methods of this nature can generate variability of data of qualitative nature, therefore the use of PLS was necessary. In this case the integration of the TISM method with the FAHP minimized this variability, because this second method uses weights based on the decision makers' preference.

According to [60], the synthesis of the TISM structure and MICMAC analyses could be considered an alternative methodology for theory building research. This methodology shows how cross-sectional data could be treated to establish causality.

4.11. AHP

The AHP method is typically used to make selections of better alternative choices. Decisions are based on the evaluation of experts and decision makers. The main benefit of the method is that the judgment values of parity comparisons are based on experience, AHP can deal with both qualitative and quantitative aspects of a decision [26]. It enables the decision maker to gain insight into the system as a whole and its components, as well as the interactions of these components and their impacts on the whole.

The disadvantage of the method is related to its inadequate application, which can occur in unfavorable environments, when the decision makers make excessive simplifications of the analyzed context. In the bibliographic portfolio only one article [26] applies the AHP method without the use of auxiliary methods. The great problem in the use of the AHP method is the formulations based on averages that, in some cases, can bring unreliable results.

4.12. Blockchain Technology (BCT)

The advantages of BCT technology in the sustainable supply chain management partnership, is that it is a set of methods embedded in software development providing a range of interaction possibilities. BCT technology is now considered a next generation information technology, a tool for sustainable supply chain management growth [37].

However, being a method unique to a technological development, it is restricted to its initial configurations. In this way the analyses are linked to the existing software resources, and it is not possible to quickly modify for custom applications.

4.13. BW-MCDM

The best–worst method (BM-MCDA) can be applied to evaluations using scales, categories or paired comparisons to obtain preferences and importance for each evaluated element [22]. The main advantage of BM-MCDA is that this method requires less data for interactions, and results in more consistent comparisons for safer results. The disadvantage of the method is that decision makers need to choose between the best and the worst item in a data set, thus generating some subjective evaluations.

4.14. Cluster Analysis + One Way ANOVA

The use of cluster analysis combined with the one way ANOVA statistical method has advantages because it is possible to classify supply chain forming clusters according to specific characteristics defined by researchers within each type of practice [32]. ANOVA analysis of variance helps to verify if there is any difference in the company's performance, because this method is able to treat various structures of experiments, besides estimating the variance with more accuracy and precision, extracting more information about the data.

As disadvantages of using these methods, it can be highlighted that the analysis of variance applied alone can limit the information, it is necessary to test sensitivity using alternative data analysis as confirmatory factor analysis.

4.15. DEMATEL

The technique studies the structure of cause and effect, analyses the relationship element "x" exerts on element "y", and the relation "y" receives over element "x" [21]. The advantage of this theory is that it does not require many variables to evaluate the relationship between the elements [58]. The downside is that it only considers the qualitative aspect of data. In this specific context [21,58] the DEMATEL method may not represent all its usefulness, since the reliability of the data becomes questionable due to the number of decision makers involved.

4.16. ELECTRE TRI

It is a method that integrates indicators for strategic environmental assessment. This method can also integrate functions that support the decision maker in the resolution process, thereby reducing the cognitive effort required in the problem modeling and analysis phase [39].

However, as it is an exclusive method of non-compensatory classification, the ELECTRE TRI is restricted to this application, requiring complementary methods to search for analysis with other objectives. These constraints may promote simpler and more limited interpretations, and often the integration of other multi-criteria or statistical methods is necessary to expand the possibilities for analysis and development of more robust results.

4.17. Fuzzy Multi-Criteria+ANP

The method consists of determining the selection criteria and their respective weights. The combination of fuzzy multi-criteria + ANP methods has advantages related to simplifying data variability.

Similar to the application of fuzzy multi-criteria combined with DEMATEL, the disadvantage is that the results cannot be replicated in other studies because the models are independent and specific to each application context [30]. In the bibliographic portfolio, only one article [30] applies the fuzzy multi-criteria + ANP method in a combined manner.

4.18. Grounded Theory

The theory is based on deriving conceptual categories grounded in evidence to collect data. The information obtained from the range of data and their peculiarities is gathered to reach the conclusion of the study [25].

The advantage lies in the possibility of analyzing whether there are correlations between the studied theory and the collected data. In contrast, the disadvantage is that this theory calls for operationalization or the need to study literature, formulate a theory, and enter the field to test the theory.

4.19. PROMETHEE

The PROMETHEE method resembles the ELECTRE method in that it originates from the same theoretical basis. In the field of sustainable supply chain management evaluation, the PROMETHEE method has advantages in formally structuring the problems, allowing for simplification of peer comparison. Another noteworthy factor is that this method allows for checking the consistencies of the assigned weights, making its application more versatile, and there is also some application flexibility in situations where numerical ranges are used to represent priorities [46].

However, PROMETHEE also has some disadvantages in the application in these contexts. One of these limitations is related to the need to change from qualitative to numerical scale, as it can significantly change the result. Other disadvantages that can occur with this method are the problems with ranking reversal in the insertion of new alternatives and data mismatch in situations with large amounts of criteria.

4.20. Rough Set Theory

The rough set theory deduces that the information about a particular subject is represented in a data set to reach the conditional performance relations [1]. The advantages of the theory include the provision of extensive relations between the environmental attributes of suppliers and business performance; the theory does not need any preliminary data or additional information about the variables; and it can be used to complement the AHP/ANP techniques. The disadvantages are that the variables for supplier development can be broad, and effective filtering of the variables is recommended to restrict the decision-making rules to a minimum.

4.21. AHP Combined with TOPSIS

The AHP method is used to set priorities for making alternative best choice selections through a set of weights assigned by decision makers. Decision analysis is based on expert and decision-maker evaluation. One of the main advantages of the method is that the judgment values of parity comparisons are based on the experiences of the agents involved. The AHP recognizes both the qualitative and quantitative aspects of a decision. The integration of the AHP result with TOPSIS is used to find the sustainable supply chain ranking [40].

However, this integration of methods may be related to their inadequate application, because by the ease of application of the methods, decision makers can generalize and oversimplify the analyzed context. For both these and other methods, the data needs to be available and reliable for application so that the result is not compromised at the end of the analysis.

This presentation of the evaluation methods used in the 43 papers of the bibliographic portfolio used to assess sustainable supply chain management reveals that there is no best or worst model for companies. Each model has its advantages and disadvantages. Some authors of the listed studies applied more than one evaluation model to reduce the negativity of a technique [18,21,23,27].

The papers of the portfolio also revealed that for the evaluation model to be successful, the information of the focal company and its suppliers and customers must be available and easily accessible [2,15–29]. The methods found in the papers of the portfolio complement each other, suggesting that future studies can analyze the integration of the assessment models fuzzy multi-criteria combined with AHP or fuzzy multi-criteria combined with ANP.

The analyzed studies show a tendency to use expert opinion together with the application of mathematical methods to produce optimal results [55]. When this combination occurs, the results are more relevant, because in the application of purely mathematical methods the preferences of the decision makers are not admitted, but when the use of this opinion occurs, the decisions can be modified, even if the mathematical methods are applied correctly.

Some studies suffer limitations regarding the application of the proposed methods [22,23,27,34]. The integration of some methods can cause problems in the research results, such as data reliability, validity of the constructs used for the study. The analysis of the articles in the bibliographic portfolio of this study helps to identify the success points of the integration of some methods, which are the advantages discussed in each method and the shortcomings of these applications.

Related to the increased need for food production to supply population growth and saturation of arable land, future studies could be developed to assess sustainable food supply chains in the agricultural environment [61]. Studies in other contexts can also be developed using combined methods that recognize the preferences of experts [55].

5. Conclusions

From the application of the proposed methodology, the results show a balance between methodological rigor and scientific relevance. Minimizing research problems indicated by Tranfield et al. [14], which classify three types of recurring problems, research with low rigor and high relevance that are called “popular science”. “Pedant science” is high in rigor but low in relevance; in turn “child science” is neither rigorous nor relevant.

This work answered the initial research question and achieved the overall objective of developing a methodology to search papers in a structured way. The specific objectives were also achieved, namely: (i) to describe each stage of this research methodology in the research procedures; (ii) to present and discuss the results using a table and observations, and subsequently provide an overview of the subject analysis of methods to evaluate environmental supply chain management applied to production engineering in journals with a high impact factor; and, (iii) by means of these results and discussions, contribute to literature on the subject of this work by listing the subjects surveyed over the last nine years on methods to evaluate environmental supply chain management with their advantages and disadvantages.

The results of this paper are valid only for the specific context in which the research was conducted, that is, scientific production of models to assess sustainable supply chain management applied to Production Engineering in Engineering III journals with the highest JCR in this discipline from January 2010 to June 2019. Thus, the results of this research cannot be used in other contexts. The research methodology, however, can be replicated in other studies using other subject matters and other keywords to create a bibliographic portfolio.

The findings of this article corroborate the development of further discussions to fill the gap highlighted by the study by Luo et al. [60] that indicated the need for theory building in sustainable supply chains. It also helps researchers describe the opportunities and challenges of applying a bibliometric methodology to sustainable supply chain management. The analysis provides a range of results that demonstrate the main methods used in the researched context, thus assisting in the development of new research and the deepening of the concepts already researched.

The theoretical contribution of this study could be highlighted by the methodology to focus on the research of methods applied in a specific research field. The articles already produced in the theme of sustainable supply chain management, bring a generalist approach so that many researchers on this subject in the field of production engineering need to treat and filter the results that interest them. Therefore, this article seeks to overcome this difficulty, motivating a debate more directed to the scholars of this specific field.

The present study assists the literature in discussing how the methods are being applied in sustainable supply chain management. One deficiency found, which needs further study, is the misapplication of analysis methods, which are applied without the judgment of the decision makers. The results showed that the integration of the subjective view of the actors involved, together with the application of mathematical models, complement each other, making the results more relevant and effective.

The present study developed its results in order to provide a directed discussion to the many researchers in the field of production engineering, avoiding the fact that these researchers need to access generalist results, which still need to be filtered to meet their interests. The study is not intended to replace any previous theory, but rather, to add analysis to the scientific debates related to sustainable supply chain performance assessment.

Another relevant contribution of this study is related to the identification of the tendency to use methods that help in understanding the preferences of the human factor in the decision process. Expert opinion motivates the reduction of deficiencies in the application of purely mathematical methods, which may differ due to the use of quantitative vision.

Author Contributions: M.L. and P.P.A.J. conceptualized the study. F.T. and C.S.M. assisted in the methodology. Analysis was executed by C.S.M., S.S.T. and A.S.G. Validation was done by M.L., P.P.A.J. and F.T. The original draft was written by C.S.M., S.S.T. and A.S.G. Review and editing were done by M.L., P.P.A.J., F.T., C.S.M., S.S.T. and A.S.G. All the authors read and approved the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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