Article

Sustainable Manufacturing: A Review and Framework Derivation

Valerie M. Scharmer *, Susanne Vernim, Julia Horsthofer-Rauch, Patrick Jordan, Maria Maier, Magdalena Paul, Daniel Schneider, Markus Woerle, Julia Schulz and Michael F. Zaeh

Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich, Boltzmannstraße 15, 85748 München, Germany; maria.maier@iwb.tum.de (M.M.); magdalena.paul@iwb.tum.de (M.P.); markus.woerle@iwb.tum.de (M.W.); julia.schulz@iwb.tum.de (J.S.); michael.zaeh@iwb.tum.de (M.F.Z.)

* Correspondence: valerie.scharmer@iwb.tum.de

Abstract: As sustainability in manufacturing becomes increasingly important, numerous concepts, new technologies, and use cases for improving and assessing sustainability in manufacturing environments are emerging. However, there is a lack of a framework that shows an easy way to identify relevant topics for action in the field of sustainable manufacturing. The purpose of this publication is to provide a structure for the topic of sustainable manufacturing, to contribute to the understanding and classification of ongoing activities, and to identify starting points for future research and development. Within this publication, an extensive literature review is presented. A framework for sustainable manufacturing that acts as a call for action for academia and operations management in the industry alike is derived from this literature review. The framework is intended for Western countries, as, within this framework, aspects such as the elimination of enslaved persons and child labor in production are assumed to be implemented through legal regulations already. Details of the framework are elaborated, and its application is discussed. This publication contributes to a common, clear understanding of sustainability and the different aspects of sustainability in manufacturing.

Keywords: sustainability; framework; production engineering; assessment; manufacturing; triple bottom line

1. Introduction and Fundamentals

The ongoing climate crisis, legislation supporting sustainable development, and increasing customer demand for sustainable products have pushed the topic of sustainability to the top of the agenda for manufacturing companies. To date, there are no widely established concepts for the implementation of sustainable practices in manufacturing available. Various tools have been created or adapted, such as the lean green movement based on lean management practices, but none of them have taken on a pioneering position in practice. Concepts, tools, or frameworks are especially scarce regarding the triple bottom line (TBL) definition of sustainability. The TBL approach requires the simultaneous and equal consideration of economic, environmental, and social aspects of sustainability [1]. Concerning manufacturing, this translates to the following definition of sustainable production: Sustainable production can be described as the creation of goods and services employing processes and systems that do not cause negative environmental impacts, that are energy- and resource-efficient, economically profitable, and that are compatible with employees, the community, and consumers [2].

To support the implementation of sustainability in production environments, this publication aims to provide a holistic framework for sustainable manufacturing. The goal is to enable academia and operations management in the industry alike to easily and comprehensively identify relevant topics in a concise framework to start action and intensify efforts depending on individual focus and strategy. The design of the framework, as a structuring of a specific topic, follows the adapted design suggestions for frameworks from Cwalina and Abrams [3], which are rooted in computer science.
to those suggestions, we aim to provide a framework that is simple to understand and adapt, aware of its trade-offs, builds upon existing frameworks, is designed to evolve, is integrable into fundamental beliefs in manufacturing, and is consistent. A framework for sustainable production is also relevant to society. The framework supports the introduction of sustainable production in a company. Sustainable production in turn supports the sustainable use of resources. This protects the environment and preserves it in the long term, which has a positive impact on society’s quality of life.

Thus, this publication presents an extensive literature review, showcasing existing frameworks for sustainability in manufacturing in general as well as sustainability assessments in manufacturing. The latter are analyzed to derive relevant categories of sustainability in manufacturing environments. The general concept and details of the derived framework are subsequently illustrated. The structure of this publication is as follows: In Section 2, the approach and the results of the literature review and analysis are displayed, including a conclusion of the identified research gap. Section 3 provides information on the approach for the framework derivation, the framework’s structure, and details on its different layers. In Section 4, the framework is discussed, and an outlook on future research is given.

2. Literature Review and Analysis
2.1. Research Methodology for the Literature Review

The research approach for the presented literature review is based on Vom Brocke et al. [4]. As many literature reviews do not fulfill the requirement of traceability and replicability, which is necessary for (re-)using the review results, Vom Brocke et al. [4] formulated guidelines for the literature search process and structured it in the framework shown in Figure 1.

Figure 1. Framework for literature reviewing [4].

(I) Definition of the review scope: In this step, the review’s general scope and goal are specified, e.g., using the taxonomy of literature reviews from Cooper [5] (Figure 2).
The focus of the review in this publication ((1) in Figure 2) lies on research outcomes, e.g., existing frameworks, systems, or other structured classifications of the topic of sustainable manufacturing, to analyze them critically and identify the central issues of this topic (2). The identified publications in the results section were clustered according to their underlying concept (3) and goal. The review was intended to provide neutral insights (4) for general and specialized scholars as well as practitioners in the field of manufacturing technology (5). The analysis intended to identify the major and most representative publications in this research area instead of giving an exhaustive literature overview (6).

(II) Conceptualization of the topic: Every literature review should give a general conception of the known knowledge base of the examined topic in the next step. Additionally, it should become clear to the readers which knowledge they need in order to understand the review and its results.

We addressed these issues by defining the relevant subject areas (sustainability, framework, and manufacturing) in the introductory section (Section 1) of this publication. Furthermore, we identified the key concepts of the topic “sustainable manufacturing” to derive suitable initial keywords for the literature search.

(III) Literature search: A structured and comprehensible process is crucial for searching the literature. For this publication, we oriented our approach on the stepwise search method developed and implemented by Vernim et al. [6] and Korder et al. [7]. As a first step, we specified our search area. To give a holistic overview of the field of sustainable manufacturing and to identify the most relevant and representative publications, we opted for a database-driven literature search, in which suitable review publications, journal publications, and conference papers were identified. Scopus was chosen as the search database, as it contains the most relevant journals in the field of manufacturing. Some initial publications about sustainability frameworks for manufacturing concerning typical terms they used for describing their focus and results were analyzed to derive promising search terms. Based on that, the search term was composed in the following way: TITLE (sustain* AND (framework OR dimension* OR assess* OR system* OR concept) AND (manufactur* OR assembl*))

The search focused on the titles of the publications to keep the search results within manageable limits in terms of quantity. Through a manual review, it was ensured that the publications were focused on the topics within the search term. The Boolean operators AND and OR allow the logical combination of search terms in Scopus. We addressed three main fields: sustainability, methodological concepts and assessments, and manufacturing. Those search fields were combined with the Boolean AND, whereas the Boolean OR combines different synonyms within one search field. We did not add any further limitations to the search to keep the results as unadulterated as possible.
(IV) Literature analysis and synthesis: We conducted the literature search until January 2022 and found 693 publications with the given search string. As a first filtering step, only publications published after 2006 were considered in the further analysis to focus on current research where sustainability in manufacturing environments started to gain attention. Next, criteria for a relevance check of the identified titles were defined. The criteria were chosen to support the focus on discrete production processes and omit supporting processes and continuous production processes.

We excluded publications with a strong focus on:

- Process, food or agricultural, textile, or semiconductor industries;
- Civil engineering or city planning;
- Raw materials extraction;
- Product development;
- Maintenance;
- Individual use cases and solutions without general or transferable results or findings.

In the second step of the literature analysis, relevance testing was performed regarding the title and, afterward, the abstracts of the remaining publications. After this relevance check, 113 publications with titles and abstracts matching the presented subjects were obtained. Of those, we analyzed the entire text in detail to decide whether the publication presented a framework for sustainability or an assessment method in a third step. Finally, 30 publications were identified for the detailed literature review, whose results are shown in Section 2.2.

(V) Research agenda: A review publication typically results in a research agenda addressing identified gaps with clearly focused questions for future research. For this publication, we focused on creating a framework that structures sustainable manufacturing holistically. The aim is to detail relevant elements and sustainability-influencing factors within manufacturing environments so that a first step is prepared for deriving company-specific improvement measures. To find such elements and factors, we reviewed both existing frameworks and indicators. While frameworks already structure the research topic in a top-down approach, indicators support a bottom-up structuring of the topic and the detailing of generic aspects of a framework. The newly derived framework for sustainable manufacturing is presented in Section 3. With this, we contribute to closing the main research gap as it will be identified in Section 2.3.

2.2. Results of the Literature Review

As described in Section 2.1, the literature was classified according to whether it contains a sustainability framework, an assessment, or both. This classification was used in Table 1, which includes all 30 relevant publications and detailed information regarding defined focus areas. Section 2.2.1 and Section 2.2.2 are also based on the classification “framework”, “assessment”, and “framework and assessment”. Only the published papers with “frameworks and assessments” are considered in both chapters. The focus areas in Table 1 were defined to meet and specify the research agenda (Section 2.1, step V), aiming to create a holistic sustainability framework that can be applied at different levels of production according to Wiendahl et al. [8] (focus area 2). Only a few publications do not consider more than one factory level. All publications considered include at least one column of the TBL (focus area 1) and a figure of a framework (focus area 3) or a list of sustainability key performance indicators (KPI) (focus area 5). Most of the publications examine the whole factory or at least more than one technology (focus area 4). The publications, which are mainly designed to describe an accounting rule or an optimization, are assigned to focus area 6. For reasons of presentation, Table 1 lists the publications with frameworks and the publications with assessments, even if focus areas 1 to 4 only apply to frameworks and focus areas 5 to 6 only to assessments. For readers who are not interested in a description of the content of the reviewed published papers, Table 1 provides an overview of the published papers’ topics.
Table 1. Overview of the literature review results and the assigned focus areas.

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<th>3. Consideration of Several Components or Key Figures</th>
<th>4. Consideration of the Factory in General or of Several Technologies and Application Areas</th>
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1: Reference does include focus area, 0: Reference does not include focus area, -: Focus area does not apply.

2.2.1. Reviewed Frameworks

In the following, the publications about existing frameworks are structured into literature-based concepts, holistic and strategic frameworks, and assessment frameworks of sustainable manufacturing.

Frameworks derived from literature reviews

In this paragraph, publications with literature-based concepts are presented that either justify a requirement for a framework or name partial aspects of a framework and are therefore assigned to the frameworks by the used research methodology (Section 2.1). Without deriving an explicit framework but concluding on the key contributors to sustainable manufacturing, Rosen and Kishawy [2] gave a literature overview of concepts, methods, and literature about sustainable manufacturing, design, and performance measures. According to the authors, sustainable manufacturing includes measures focusing on product, process, and practices, whereby defined procedures, management and culture, information (quantitative and qualitative) and its assessment, and models or frameworks are necessary for implementing sustainability in manufacturing. Furthermore, reference is made to different design approaches and indicator sets, and the need for a framework for sustainable manufacturing is pointed out. Through another extensive literature review, Moldavska and Martinsen [15] provided a list of criteria for sustainable manufacturing based on the presented operational definition of sustainable manufacturing using a trajectory attractor (an approach used for complex socio-economic systems) as a metaphor. The provided criteria offer a behavior pattern towards which manufacturing companies should evolve. Furthermore, the criteria can guide the selection of sustainability indicators for different organizations. No specific use case or industry was analyzed, and no particular framework was derived. Sutherland et al. [18] examined how manufacturing affects society by exploring national-level social indicators, frameworks, and principles. The research was based on literature reviews with particular attention paid to the following
four criteria: (i) investigated social indicators and frameworks, (ii) effect of manufacturing on social performance, (iii) social life cycle assessment methodology, and (iv) integration of social, environmental, and economic considerations. The social needs are categorized into stakeholders and subcategories with indicators. The authors exclusively focused on the social pillar of sustainability and did not derive a new framework.

**Holistic and strategic frameworks**

In addition to the publications that are based on a systematic literature review that concludes in structured overviews regarding sustainable manufacturing, published papers focused on the intersections and dependences between sustainability aspects. Valase and Raut [19] built a structural equation model based on a so-called SMEET (social, manufacturing, environmental, economic, and technology) framework for sustainable manufacturing. The main objective was to determine and discuss the relationship between the mentioned modules of the framework. The study has been carried out with a literature review, a questionnaire, and a validation of the model considering different Indian companies. Jain and Kibira [14] presented a system model with sustainable manufacturing artifacts and their influences and dependencies based on the following four domains: financial, environmental, social, and manufacturing. Following the logic that sustainable manufacturing is a multi-complex problem, the authors applied multi-resolution modeling for each domain based on different sustainability measures. No evaluation and no use cases were given.

In addition to the mentioned publications, the observed literature consists of published papers with holistic frameworks for sustainable manufacturing, e.g., Bastas [9] analyzed 98 publications and conducted a descriptive and thematic analysis of the literature to answer the research questions about the latest trends, technology research areas, dimensions, indicators, challenges, requirements, and direction of sustainability manufacturing. After defining the research strategy and questions, the literature search, its evaluation, and selection followed. The literature analysis includes the distribution of publications across the publication year, country, and research methodology, as well as across the technology areas and the sustainability dimensions. A conceptual framework of sustainable manufacturing technology research was derived to structure the selected research trends and literature-based findings. System and process design, along with manufacturing processes, are fundamental to the pillars of digital manufacturing and sustainability assessment. Furthermore, sustainable manufacturing technologies are positioned as the framework’s core, contributing to the primary goal of achieving TBL sustainability. Finally, the author emphasized challenges and future directions in the research field concerning the need for inter- and transdisciplinary engagement, sectoral dissemination, expansion of the scope, and a holistic approach to TBL sustainability. Furthermore, Dassisti [10] presented, following a scientific literature analysis, a systemic view on recent sustainability-related concepts in manufacturing and classified the identified approaches based on games theory. The proposed framework visualizes efforts made by scientific research on sustainability and gives a classification of the scientific contributions to sustainable manufacturing. However, as stated by the author, the work has several limits, such as selecting “classification methods based on the author’s personal intuition and judgment”. Considering the environmental pillar, Yuan et al. [21] introduced a three-dimensional system approach (technology, energy, and material) to enhance sustainable manufacturing. Calculation rules for material and energy are presented, and material/energy flow modeling is introduced for evaluating sustainable technology. The manufacturing process of atomic layer deposition as a use case of industrial-scale manufacturing was chosen to compare different energy sources regarding CO₂ emissions and materials in terms of the human health index. With the main focus on Industry 4.0 in the context of sustainable manufacturing, Sartal et al. [17] gave an overview of sustainability concepts in the manufacturing sector. The authors discussed current trends, similarities, and contradictions in research based on a literature review. They concluded in a framework considering a circular process including the design, the manufacturing, and the use phase in a socio-economical system combined with an environmental system. Another published paper focused on several life cycle phases was
presented by Busch and Graberg [34]. The so-called ESG factors (environmental, social, and governance) are supplemented by the financial factor, assigned to the life cycle phases, and thus a framework is created. Nine product- or company-related fields of action are defined to achieve the goals of the three life cycle phases: sustainable product–service systems (development phase), sustainable value-added processes (production phase), and sustainable product use (use phase). The company-related action areas consider digitalization (1), sustainable organizational structure design (2), and sustainable resource allocation (3). The assessments of sustainable performance (4), product–service system design (5), supply chains (6), and supply processes (7) are introduced for the development and production phases. In the user phase, the product life cycle extension (8) and the customer process’s sustainability enhancement (9) are described.

A different approach to holistic frameworks was presented by Moldavska and Welo [38], who reviewed existing definitions of sustainable manufacturing representing the common understanding of sustainable manufacturing and derived a framework based on that. The framework contains three layers: The first is the perspective layer, which represents the most important aspects when practicing sustainable manufacturing. The second layer consists of application domains (e.g., product, process, technology, etc.), which are the focus of actions. The third layer distinguishes approaches into objectives, i.e., whether the goal is to enhance or decrease certain aspects.

Among the frameworks identified, two focus on strategic aspects of sustainable manufacturing in particular. Hussain and Jahanzaib [13] developed a framework for the organization of the transformation towards sustainable manufacturing in companies. The framework consists of three steps: The first step is to determine the ideal state of the company (sustainability of society, environment, and economy), and the second step is to select a strategy, where the framework provides information about the interrelationships in sustainable manufacturing. The last step contains the architecture, where the structure, the processes, and the activities necessary to reach sustainable manufacturing are defined. Ocampo and Clark [16] proposed a framework that unifies sustainable manufacturing and manufacturing strategies to support decision-makers in identifying policies that facilitate sustainable manufacturing. The framework is based upon manufacturing strategy systematization and adds sustainable aspects, with the framework’s core being manufacturing decision criteria and the impact other strategic aspects have on these criteria.

Frameworks facilitating assessments

Furthermore, seven publications containing frameworks on assessing sustainability in manufacturing have been analyzed. Saad et al. [36] provided an overview of elements relevant to sustainability in manufacturing and conceptualized an assessment scheme where the three sustainability levels of process, product, and system are examined. The five main elements in the sustainability assessment are manufacturing costs, energy consumption, environmental impact, waste management, and personal health and safety. Yusup et al. [39] developed a conceptual framework for determining the sustainability performance of manufacturing processes. The framework reduces the assessment of the three pillars of sustainability to six fundamental aspects: design, material, process, quality, safety, and competence, which represent levers for improving sustainability performance. Eslami et al. [35] presented a survey on sustainability dimensions and sub-dimensions in manufacturing based on a systematic literature review, content analysis, and formal concept analysis. Through the literature review, the authors provided an overview of the mentioned dimensions of sustainability and an overview of corresponding sub-dimensions for the three most referenced dimensions: environmental, social, and economic. Furthermore, the authors conducted a formal concept analysis to further evaluate the sub-dimension interdependencies within the environmental dimension. Gbededo et al. [11] used a systematic literature review to demonstrate the transition from segmented analysis methods to a more comprehensive and integrated life cycle analysis approach. The authors developed a theoretical approach that provides a roadmap for developing an integrated conceptual modeling framework that can be used to derive guidelines for developing a
holistic simulation model. All three sustainability dimensions are addressed. The proposed framework is divided into two phases: In the first phase, the objectives and the framework are defined with respect to the Sustainable Product Development dimension before the problem definition and objectives are formulated concerning aspects of sustainability in the second phase. Giovannini et al. [12] presented a product-centric ontology, associating concepts of products, processes, resources, and sustainable manufacturing knowledge. The knowledge-based system is supposed to simulate a sustainable manufacturing expert, enabling companies to identify and propose change opportunities in manufacturing automatically. The developed concept was applied at a multinational company producing air conditioning and refrigeration units for industrial use. Waltersmann et al. [20] developed a benchmark method using a factory framework. A system of 146 indicators for the benchmark was derived from established approaches and sorted by the categories of material, energy, emissions, staff, and organization. The work includes a case study with a company from the automotive sector, which shows the applicability and benefits of the developed benchmark. Based on a structured literature review, Sangwan et al. [37] derived an organizational sustainability readiness assessment methodology that contains a questionnaire with a focus on the critical factors of policy, product, and process. The questions are structured along material, energy, infrastructure, water, air, people, and money as resources of sustainable manufacturing. In addition, a sustainability assessment of manufacturing organizations with an indicator set was introduced that covers the levels of life cycle assessment, the mentioned resources, the critical factors, and the sustainability dimensions.

The analysis of the existing literature on frameworks shows that most publications focus on ways to assess the sustainability of a manufacturing company. In comparison, only a few frameworks describe sustainability in manufacturing companies holistically. The concept of the TBL is mainly considered. Nevertheless, only a few publications provide detailed information on specific measures or validation. The frameworks are largely literature-based and offer a structured overview of sustainability in manufacturing but show a lack of detail in framework components and applicability. So far, no framework has been established as a standard for research and industry, yet. Sustainability in manufacturing companies thus remains intangible.

2.2.2. Reviewed Assessments

In addition to the presented frameworks, the discussion of sustainability assessment is the topic of a large part of the literature results. The approaches usually contain indicators that are categorized according to different attributes. The resulting classification principles can also be used to derive interesting aspects of sustainable manufacturing. Therefore, in the following, the relevant works with a focus on the organizational frameworks are presented.

Based on four indicator frameworks, Tan et al. [32] identified 40 sustainability indicators for small- and medium-sized manufacturing enterprises. Four internationally recognized sets of indicators, totaling 405 indicators, were analyzed. Key indicators were selected through a systematic process that included an elimination process based on expert opinion and a feedback loop with industry input to assess the applicability of the indicators to the manufacturing industry. The framework was customized specifically for small- and medium-sized enterprises in Singapore. The 40 sustainability indicators included are organized by dimension, subcategory, indicator, unit, suggested quantification method (yearly), and goal. Paralleling this effort, Park and Kremer [28] provided an overview of common environmental sustainability indicators, a categorization of these indicators based on text mining, and a ranking of their usability and utility. The publication presents the 55 identified environmental indicators, a clustering of the indicators into 5 categories, and a ranking of each indicator’s current use, potential use, usefulness, and practicality. The categories used to group the 55 indicators are environmental impact and chemical release, pollution from emissions and waste, end-of-life management and chemicals usage, raw materials and facility management, and energy and water management. The findings were
not limited to any particular industry. Combining the two manufacturing concepts of lean manufacturing and cleaner production, Ramos et al. [30] developed a lean and cleaner production benchmarking method. The developed method aims to understand how companies act in terms of cleaner production and which lean manufacturing methods they apply. The application of the method allows the evaluation of how and to what extent companies contribute to a more sustainable way of manufacturing. The assessment measures six variables: management/responsibility, people, information, supplier/organization/customer relationship, product development, and production processes. They applied the method in a benchmarking study of 16 Brazilian manufacturing companies. Windmark et al. [33], in comparison, presented a framework for assessing sustainable production based on the existing cost model [40]. The authors evaluated a process-oriented, performance-based cost model for manufactured parts [40] for its ability to capture sustainability. Based on a literature review, 108 sustainability indicators were identified and compared to the input parameters of the process-based cost model by Ståhl et al. [40]. The developed framework complements the monetary parameters of the cost model with qualitative parameters for the assessment of sustainable production and sustainable decision-making. It allows the collection of information on all three dimensions of sustainability for small- and medium-sized enterprises and larger companies, with a particular focus on the manufacturing perspective. Aiming at a methodological and structured approach, Swarnakar et al. [31] developed a conceptual method for assessing the sustainability of manufacturing processes. For this purpose, the authors first identified and categorized a set of 40 empirically tested sustainability indicators covering all dimensions of the TBL before integrating them into the value stream mapping process. The applicability of the developed conceptual method was evaluated by applying it in two manufacturing companies, and Lean Six Sigma experts analyzed potential improvement opportunities. In contrast, in the study presented by Petry et al. [29], a systems approach was used to examine four underlying linkages between the pillars of sustainability and quality in the sustainability assessment of manufacturing systems. The authors used a dynamic sustainability assessment as their research’s basis and used different cost modeling approaches to assess the quantitative relationships between the factors studied. The four main relationships examined are quality and economic, environmental and economic, social and economic, and social and environmental interactions. A case study in a manufacturing company was used to test the applicability of the assessment. Pursuing two objectives, Cai and Lai [22] presented an approach for sustainability benchmark assessment: Firstly, they want to overcome performance quantification and hierarchization deficiencies of existing assessment approaches. Secondly, they elaborated a conceptual model demonstrating efficiency advantages realized by sustainability assessment. Based on a literature review, sustainability indicators were collected and used to build a “Sustainability integrated model [and] benchmark”. The sustainability indicator system encompasses the aspects of energy, economy, and environment. Two concepts for a sustainability benchmark and a sustainability benchmark rating were proposed. The goal is to facilitate the sustainable performance quantification and hierarchization of mechanical manufacturing systems. The developed approach was applied to a small mechanical manufacturing enterprise in China. Drafting an indicator system, Digalwar et al. [23] support social sustainability assessment in the machining industry in India. Starting with a literature review about relevant topics in social sustainability, a representative survey was conducted to find the essential indicators for the industry. After identifying the problem of measuring social sustainability compared to ecological and economic sustainability, 14 indicators were identified through a literature review. These indicators are divided into four groups: workplace condition, workplace environment, work safety and training, and skill development. By carrying out a survey in the industry, the indicator groups were weighted according to their importance, and an equation for a social sustainability indicator was given. Following a mathematical modeling approach, Garbie [24] proposed a concept for assessing manufacturing companies’ sustainability practices and implementation. For this purpose, a literature review was conducted, based
on which four individual frameworks for performance measurement in the area of sustainability were identified: sustainability awareness, sustainability drivers, sustainability barriers, and relevance of sustainability indicators. After aggregating the frameworks in an analytical model, a real-life case study was carried out to demonstrate the proposed frameworks. The research is not limited to a certain industry or use case. Respectively, Helleno et al. [25] presented an approach to evaluate sustainability KPIs integrated into the value stream mapping of manufacturing processes. After executing a literature review with the keywords sustainability, sustainability KPIs, and lean, they selected sustainable KPIs and followed an evaluation method. By applying the method to three case studies, an analysis for improvement was executed with the method. For each dimension of the TBL, a level of sustainability is calculated based on KPIs. The KPIs are quantified using value stream mapping and additional interviews to evaluate indicators that cannot be seen directly on the shop floor. Based on the calculated level for the use case, improvements are discussed with the management. Huang and Badurdeen [26] presented a literature-based metric to evaluate each aspect of the TBL according to companies’ hierarchy levels. They focused on system metrics, which assign the aspects of the TBL, a sustainability enhancement methodology, and the total life cycle focus methodology to the perspectives of product, process, and company to evaluate sustainable manufacturing. The introduced system metrics are divided into the four levels line, plant, enterprise, and supply chain. The enterprise level is presented in more detail and connected with KPIs. Finally, the general metric concept was evaluated with the data of a consumer electronics manufacturer in the USA. The publication of Huang and Badurdeen [27] presents a metric to evaluate aspects of the TBL according to companies’ hierarchy levels with a focus on the evaluation of the line level. Based on a literature review and earlier studies, a metric for the line levels is presented and evaluated by using two scenarios. The metric includes clusters to evaluate the status quo for each TBL dimension on the line, plant, or enterprise level. For this, KPIs are identified, and a process is defined as to how they should be measured, normalized, weighted, and aggregated for each hierarchy level. For evaluation, a satellite television manufacturer and a consumer electronics manufacturer in the USA are used. Saad et al. [36] provided guidance on selecting and quantifying relevant sustainability indicators. In addition, they developed a framework (Section 2.2.1) that also captures interactions between different indicators by applying multi-criteria decision-making methods. The presented indicators are grouped into different categories, covering all dimensions of the TBL, technological advancement, and performance management. Lastly, Sangwan et al. [37] presented various key performance indicators and their relationship to sustainability dimensions as part of a comprehensive sustainability readiness assessment methodology previously discussed in Section 2.2.1. The provided indicators are categorized into the following groups: people, money, material, energy, Infrastructure, water, and air.

In summary, extensive research has been conducted to evaluate the sustainability performance of manufacturing systems using different approaches. Several other publications, including Schneider et al. [41], Finnveden and Moberg [42], Ness et al. [43], Moldan et al. [44], Singh et al. [45], and Ahmad et al. [46], have provided insights into the current state of the art of sustainability assessment. It is evident that sustainability assessment systems serve different purposes, ranging from supporting decision-making processes to supporting operational changes and assisting in conceptual design phases [41,44]. Various assessment methodologies have been identified to systematize these systems [41–43,45]. Furthermore, existing sustainability rating systems have been categorized based on the levels of the company considered and the sustainability dimensions covered [41,46]. However, challenges persist in dealing with sustainability assessment systems. First, there is a consistent lack of a universally applicable sustainability concept that is suitable for different sectors [47]. Second, there is ongoing disagreement on fundamental aspects of the taxonomy of sustainability indicators. This aspect primarily concerns the dimensions and operational levels to be considered in the assessment, e.g., there are few approaches that comprehensively address all three dimensions of TBL sustainability at the segment/system,
cell, and station levels of a company. Often, these levels cover only environmental and economic aspects, or in some cases only environmental factors, with limited consideration of social factors.

2.3. Research Gap

The literature review results from Section 2.2 showed that numerous works and publications related to sustainable manufacturing are intended to structure this broad topic with the help of different frameworks. Additionally, they are presenting methods and indicators for assessing current sustainability efforts within companies. Nevertheless, most of them are facing some of the following issues leaving gaps in the current state of research:

• Focus on specific parts, layers, or industries within manufacturing instead of giving a holistic overview;
• Lack of details when it comes to describing sustainability factors within the manufacturing environment, including technologies for implementing sustainability, considering different organizational (strategic, tactical, operational) and structuring (from network to shop floor) levels of a factory, and taking different phases of a life cycle into account;
• Considering only single parts of the TBL (especially social sustainability is considered separately, along all organizational layers of production);
• Lacking a link between activities on the shop floor and their influence on the overall sustainability of manufacturing companies;
• Missing cross-sector sustainability concept.

This publication aims to close the upper-listed research gaps and is designed to fulfill the following criteria:

1. The newly presented framework addresses sustainable manufacturing holistically (in terms of TBL and level in the company), independent of the industry sector with a focus on discrete manufacturing.
2. The newly presented framework specifies the relevant elements and indicators influencing the overall sustainability of manufacturing environments.
3. With a generic indicator catalog, the newly presented framework offers a starting point for researching and defining company-specific sustainability improvement measures.

As none of the publications we reviewed so far fulfill all those criteria, we created an adapted framework, which is detailed in the following section.

3. Derivation of the Framework

To offer information and support for both academia and operations management in the industry, we created a new framework that addresses all levels of manufacturing, provides the relevant sustainability indicators in those fields, and, at the same time, offers an approach to derive concrete recommendations for action based on KPIs and data from the shop floor. We developed a level-based concept for the new framework in several brainstorming rounds and workshops. Scientific researchers with expertise from industry and research projects in the areas of circular economy, energy and resource efficiency, life cycle assessment, and sustainability assessments were involved in the development process. The structure and design of the derived framework are described in the following section.

3.1. Framework for Sustainable Manufacturing

Figure 3 depicts the newly generated framework for sustainable manufacturing that consists of multiple layers, each representing a different aspect of the manufacturing process. The layer approach was chosen because the structure is familiar to both academia and operations management in the industry, ensuring easy access to the framework. Based on the research gap defined in Section 2.3, the concept of knowledge development by North and Kumta [48] is chosen as the structuring base for the framework. The knowledge devel-
our framework consists of analyzing the data generated on the shop floor and evaluating the current state of sustainability based on that information. For this, sustainability indicators are used. In conclusion, this layer is crucial for identifying areas where sustainability can be improved and for deriving specific measures to achieve sustainability goals.

Figure 3. Framework for sustainable manufacturing.

The first stage of knowledge development involves acquiring information consisting of collecting data or gathering information from various sources. In our framework, the shop floor represents this bottom layer, which consists of all the specific manufacturing processes involved in creating goods, i.e., this is the layer where raw materials are transformed into finished products and where most of the data related to manufacturing processes are generated. The data can include information about, e.g., the machine’s energy consumption or waste production during a specific process step.

Once the data have been acquired, it needs to be analyzed, patterns have to be identified, and relations have to be identified to create coherent information and understanding and, thus, to interpret it to extract meaning and insights. Therefore, the next layer of our framework consists of analyzing the data generated on the shop floor and evaluating the current state of sustainability based on that information. For this, sustainability indicators are used. In conclusion, this layer is crucial for identifying areas where sustainability can be improved and for deriving specific measures to achieve sustainability goals.

The following two stages of knowledge development derive concrete measures for action from the knowledge gained, aiming to transform these into competent actions to achieve a specific overarching goal. This knowledge stage can involve developing new theories, frameworks, or models that help to explain and predict phenomena in a particular field. New knowledge that is created can then be used to inform decision-making, to guide action, and to drive innovation in the action stage. The top of the pyramid, the North Star, is not a layer but the future scenario of a fully sustainable manufacturing company.

In the new framework for sustainable manufacturing, the top layer represents the goal of achieving a truly sustainable way of manufacturing goods. To reach the top layer, the knowledge gained about the current sustainability status on the shop floor needs to be transferred into targeted actions to improve sustainability.

Overall, the framework is designed to provide a structured approach to sustainable manufacturing by breaking down the complex sustainability improvement process with its numerous influencing factors and indicators into manageable layers and ensuring that all aspects of sustainability are considered at each stage. By following this framework, manu-
facturers can take a systematic approach to improving sustainability and thus ultimately achieve their sustainability goals.

3.2. Description of the Two Lower Framework Layers and Related Indicators

3.2.1. Description of the Layer “Manufacturing System & Data”

The first layer describes the manufacturing system and the corresponding data. It represents the shop floor physically and digitally. It interacts with its environment through its core components of products, employees (human labor; directly influenced by production management), sites and area (operating resources; indirectly influenced by production management), and means of production (operating resources and materials; directly influenced by production management). Details are provided in Figure 4. These core components are either influenced by factors from the environment or have an impact on the environment. These influencing factors and impacts can serve as starting points for efforts to increase sustainability in manufacturing. For the core aspects, the categorization of production factors introduced by Wöhe et al. [49] was adjusted to identify human labor, operating resources, and materials as the main production factors. The interdependencies between production factors and their environment were derived from the existing frameworks and definitions.

Figure 4. Detailed view of the layer “manufacturing system & data” in the framework for sustainable manufacturing.

Regarding the core component of employees, the aging society and the sense of purpose are influencing factors. The former relates to the aging workforce in Western societies that is already forcing companies to rethink job contents, organization, and automation to account for a smaller and older workforce. Sense of purpose refers to an increased demand for finding meaning in the job, which can either be fulfilled by a company’s vision that aligns with the employee’s aspirations, the job content itself, or a great sense of belonging. Impacts on the environment are the financial wealth created through fair wages and compensation as well as providing training that increases employees’ education level.

With respect to the core component means of production, the main influencing factors are technological innovations as well as materials and resources. Technological innovations must be scouted and can be implemented to increase the efficiency and effectiveness of machinery, materials, and resources in manufacturing. Materials and resources enable the production of goods. Carefully selecting and sourcing materials and resources influences manufacturing and product sustainability. The means of production impact the environment through waste and emissions. Also, technological innovation can be created within manufacturing and support other companies or stakeholders in increasing sustainability.

The core component sites and area impact the environment through community prosperity and land consumption. Sustainable manufacturing can greatly support community
prosperity through wages and taxes. Nevertheless, it may also negatively impact community prosperity if community resources are depleted or polluted. Land consumption might also contribute to depletion or pollution or consume areas otherwise available to nature or for farming. The component of sites and area is influenced by the supply chain, regulations, and the energy mix. The supply chain affects how much transport is needed to fulfill relevant tasks. Regulations define the general conditions in which manufacturing is facilitated. And finally, the energy mix of a site influences the emissions allocated to manufacturing processes.

The list of influencing factors and impacts for the core components is not exhaustive but provides a starting point for optimizing manufacturing regarding economic, ecological, and social sustainability.

The first layer of the framework furthermore communicates with the layer above, the indicator layer. Information is passed on to the second layer in the form of data, where the data are utilized to provide indicators. These indicators are then passed back to the shop floor to support the organization and optimization of manufacturing.

3.2.2. Description of the Layer “Indicators”

Based on the indicator lists from the publications in Section 2.2.2 on manufacturing-dependent indicators, a proposition for an indicator catalog was developed. The publications by Cai and Lai [22], Digalwar et al. [23], Garbie [24], Helleno et al. [25], Huang and Badurdeen [26], Huang and Badurdeen [27], Park and Kremer [28], Petry et al. [29], Ramos et al. [30], Swarnakar et al. [31], Tan et al. [32], and Windmark et al. [33] are used for the description of the indicator layer.

Duplicative or similar indicators have been combined and slightly renamed where necessary. Indicators related to costs were modified and replaced by those describing consumption and sustainability in manufacturing. In addition, indicators were not considered if they could not be applied to describe Western manufacturing environments, i.e., basic compliance with prohibitions, such as prohibition of child labor, is assumed. The proposed indicator catalog consists of 34 indicators and can be seen in Table 2. The indicator catalog does not claim to be exhaustive. Instead, it is intended to give examples of manufacturing areas in which sustainability plays a role.

The indicator catalog was then integrated into the developed framework by assigning the corresponding indicators for each framework component during a structured workshop by the authors. The indicators can be directly related to one or more framework elements. Thus, 19 indicators address the system element employees, 39 indicators the element means of production, and 9 indicators the element sites and area.
Table 2. Integration of the indicator system into the framework for sustainable manufacturing.

<table>
<thead>
<tr>
<th>TBL Aspect</th>
<th>Employees</th>
<th>Means of Production</th>
<th>Sites and Area</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Consump.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Reused and Recycled</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Environmental Accidents</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Less Harmful Materials</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Recycled Material Consumption</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Packaging</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Energy Consumption per Product</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Ecological Production (including Stand-by)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Energy Consumption in Logistics</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Waste Energy Emission</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Renewable Energy Consumption</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Solid Waste Mass (hazardous and non-hazardous)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Emissions to Water (hazardous and non-hazardous)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Reusable Packaging Emissions to Air (including Greenhouse Gases)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Environmental Management System</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Production Resource Efficiency</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Quality Scrap</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Set Up, Takt, and Cycle Times</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>TBL Aspect</td>
<td>Indicator</td>
<td>Employees</td>
<td>Means of Production</td>
<td>Sites and Area</td>
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<tr>
<td>Social</td>
<td>Absenteeism</td>
<td>x</td>
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<td></td>
<td>Accidents and Injuries</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>Satisfaction and Turnover</td>
<td>x x</td>
<td>x</td>
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<td>Employment Growth</td>
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<td></td>
<td>Exposure to Hazards</td>
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<td></td>
<td>Fair Wages and Compensation</td>
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<td></td>
<td>Level of Education</td>
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<td>x</td>
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<tr>
<td></td>
<td>Diversity in the Workforce</td>
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<td>x</td>
<td>x</td>
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<td></td>
<td>Noise Level</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td></td>
<td>Employees’ Associations for Collective Decision-Making</td>
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<td>x</td>
<td>x x x x x x x x x x x x x x x x x x x x</td>
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<td></td>
<td>Physical Load of Employees</td>
<td>x x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Training Opportunities for Employees</td>
<td>x</td>
<td>x</td>
<td>x x x x x x x x x x x x x x x x x x x x</td>
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</tbody>
</table>

Table 2. Cont.
4. Conclusions and Outlook

The increasing severity of the climate crisis, evolving sustainable development legislation, and growing customer demand progressively drive manufacturers to prioritize sustainability. Although the TBL concept provides a direction for sustainability initiatives, existing sustainability frameworks based on this principle are inadequately developed. Despite the numerous proposed frameworks and assessment methods for sustainable manufacturing, we identified several relevant gaps. These gaps include a prevalent lack of a holistic view, with most models focusing on specific parts, layers, or industries. Insufficient detail is provided on sustainability factors in manufacturing. Moreover, the TBL consideration is often incomplete, particularly concerning the aspect of social sustainability across production layers. There is a noticeable disconnect between shop floor activities and companies’ overall sustainability. Finally, a cross-sector sustainability concept is missing.

This publication proposes a holistic sustainable manufacturing framework intended to support academia and operations management in the industry in identifying relevant topics for action. The developed framework is based on the knowledge development concept by North and Kumta [48], which illustrates the transformation of raw data into knowledge. The proposed framework breaks down the complex process of sustainability improvement into two manageable layers, ensuring that all aspects of sustainability are considered. The first layer of the framework represents a specific manufacturing system and corresponding data. The subsequent indicator layer focuses on interpreting and evaluating data from the manufacturing system to understand the current state of sustainability. Practical support to implement the framework is provided by detailing the indicator layer and the assignment of the indicators to the components of the production. To improve the aspects measured by the suggested indicators towards a more sustainable way of manufacturing, the implementation of typical Industry 4.0 technologies like Big Data Analytics, Artificial Intelligence (AI) or the Industrial Internet of Things (IIoT) is beneficial [50]. In their articles, Ng et al. [51] and Fuertes et al. [52] gathered an overview of how Industry 4.0 trends and their constituents are able to improve the economic, social, and environmental performance of manufacturing companies. Future research should evaluate the specific contribution regarding each aspect measured by the suggested indicators to support practitioners in the targeted application of available Industry 4.0 technologies.

To facilitate the shift towards sustainability in practice, we have chosen the familiar and low-threshold approach of manufacturing levels. Here, practitioners from operations management can find accessible aspects to start their sustainability journey without becoming overwhelmed with the complexity of the topic. The pyramid visualization helps to understand the cooperation and support needed throughout the company to holistically embed sustainability. This also requires committed management, which provides the necessary resources to make production more sustainable. Our framework has been derived from literature and experiences from case studies in academia and industry but has not yet been implemented. It is therefore an invitation to academia to detail, implement, and validate the provided framework. However, this approach has limitations. The list of influencing factors and indicators for core components in the framework is not exhaustive, thus serving merely as a starting point for optimizing manufacturing in terms of economic, ecological, and social sustainability. The validation of this new framework will be an area of future work, as it will require further application and testing to refine and enhance its efficacy.

Author Contributions: Conceptualization, V.M.S., S.V. and J.H.-R.; methodology, S.V. and J.H.-R.; literature review, all authors; writing Section 1, J.H.-R.; writing Section 2.1, S.V. and J.H.-R.; writing Section 2.2, V.M.S.; writing Section 2.2.1, J.S. and M.P.; writing Section 2.2.2, M.M., M.W. and D.S.; writing Section 2.3, S.V.; writing Section 3, S.V., J.H.-R. and V.M.S.; writing Section 4, P.J. and V.M.S.; review and editing, P.J., V.M.S., J.S. and M.F.Z.; visualization, J.H.-R., S.V. and V.M.S.; supervision, M.F.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the German Federal Ministry of Education and Research (BMBF) for funding and Jülich Project Management for supervising the SynErgie project (03SFK3E1-3).
Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

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