Simulation of Hospital Waste Supply Chain in the Context of Industry 4.0—A Systematic Literature Review

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Abstract: Supply chain management is a crucial task for all companies, as it is essential to respond to increased demand and competitiveness. An exponential increase in hospital waste can cause very significant risks to both humans and the environment if it is not treated adequately. In this way, the efficient management of this waste can bring benefits and prevent an increase in the likelihood of disease occurring. With the growth of technology, there are various tools available to improve decision-making in the supply chain. Simulation, one of the pillars of Industry 4.0, is one of the tools being used. With the complexity of systems increasing, hybrid simulation provides more precise solutions to problems. The aim of this article is therefore to systematically research and analyze the literature on the use of simulation/hybrid simulation in supply chains in the health sector. In this way, 20 articles that approach simulation as a decision support tool in hospital waste supply chains were analyzed in the context of Industry 4.0. The results indicate that the years 2020 and 2023 had the highest number of publications (with five each) and that countries such as China and Indonesia had the highest number of documents on this topic (with five each). The topics in this research area with more related documents were environmental sciences, computer sciences and medicine. This research highlights the fundamental role of simulation approaches in improving the performance of supply chains in the healthcare sector, promoting resilience and improving healthcare outcomes for patients.

Keywords: medical waste; supply chain; industry 4.0; simulation; systematic literature review

1. Introduction

The increase in population has led to an expansion in global spending on healthcare, making it one of the fastest growing industries in recent years [1,2]. The health sector has grown exponentially due to increased public awareness and globalization [3]. Hospitals, nursing homes and various pathology laboratories have contributed to the increase in hospital waste, which includes syringes, scalpels, bloody cottons and chemicals, leading the World Health Organization to consider this type of waste a non-hazardous municipal solid waste [4]. Medical waste has increased with the increase in the world’s ageing population, but also with the emergence of the COVID-19 pandemic [5]. It is estimated that the amount of medical waste generated by the COVID-19 pandemic was 2.6 million tons per day worldwide [6]. Medical waste includes all solid and liquid waste produced in the treatment, diagnosis and immunization phases of both animals and humans [7]. Hospital waste is the second most dangerous type of waste in the world, and second only to radiation waste [8]. Medical waste contains a wide variety of microbial contaminants and chemical compounds, making it essential to take particular care to increase...
prevention and reduce the transmission of diseases and viruses [9]. The inappropriate use and disposal of hospital waste is known to be a source of preventable infection and demonstrates low levels of management [10]. It is projected that healthcare waste management costs will grow by 5.3% annually (USD 11.77 billion in 2018 to USD 17.89 billion in 2026) [11]. Although health services increase people’s life expectancy through the treatment and prevention of diseases, they generate a large amount of medical waste [12].

Therefore, due to the consequences of the improper use and disposal of medical waste, it is necessary to take additional care when it comes to managing a hospital waste supply chain. As a result, with advances in technology, there are tools that make it possible to analyze waste more carefully, such as simulation, which makes it possible to create various scenarios to ascertain which is the best for decision-making, thus reducing the risk of infection.

The objective of this article is to carry out a systematic search of the literature and a bibliometric analysis that studies and analyzes similar works on the subject of hospital waste supply chain management through simulation.

This article is divided into six sections. Section 1 presents a brief overview of the central themes and aim of the article. Section 2 presents a literature review of the topics. Section 3 describes the methodology used to conduct this study. Section 4 contains the results of an analysis of the studies chosen according to the criteria. Section 5 discusses further themes. Finally, Section 6 provides some limitations about the work and also presents the final conclusions.

2. Literature Review

2.1. Industry 4.0

The need to constantly adapt and use new technologies has forced industry to evolve into a new era, giving rise to a new industry: Industry 4.0 [13]. The concept of Industry 4.0 was mentioned by the German government’s initiative in 2011 as a strategy for production in the country’s industrial sector [14]. The main goal of Industry 4.0 is to improve the operational performance, efficiency and effectiveness of a given company by digitizing and connecting machines and equipment [15]. The objective of Industry 4.0 is to transform machines into self-aware machines in order to increase overall performance [16].

The implementation of Industry 4.0 enables both the horizontal and vertical connectivity of people, equipment and objects based on the Internet in real time, making it possible to solve the various challenges that companies are currently experiencing [17]. Industry 4.0 makes it possible to connect industry through an internal and external supply chain network in a digital way [14].

Industry 4.0 makes it possible to develop and improve the competitiveness of companies by producing a finished product that is of higher quality, is more comfortable, and is cheaper to use and maintain [18]. One of the fundamental principles of Industry 4.0 is the interconnection between processes and machines so that data can be collected, exchanged and analyzed to prevent future behavior, as well as to solve problems [19].

2.2. Healthcare Waste Management

The management of medical waste is one of the most complex and demanding tasks facing managers as the population grows and the demand for medical services rises [20]. The poor management of healthcare waste has negative effects on the environment and public health [21,22]. Waste management is a complex process consisting of the collection of medical waste, the identification of the transportation route, the location of the disposal site, the selection of the treatment technology and, finally, the recovery of valuable energy [23].

The main objective of medical waste management is to manage, reduce and eliminate biological and chemical problems [24]. Effective supply chain management is a challenge
in the various sectors of a given organization; however, the complexity of managing a hospital supply chain is greater and requires more attention as it directly influences the safety and health of those involved [25]. Poor medical waste management can lead to the transmission of AIDS, hepatitis, typhoid fever and many other infectious diseases [26].

With an increase in spending on the treatment of medical waste, medical organizations have attempted to minimize costs and maintain good-quality medical services and dispose of infectious waste legally by selecting qualified companies for the disposal of medical waste [27]. Advances in technology, transportation and trade have allowed for global economic growth, also increasing the demand for medical equipment, but have nevertheless led to a gradual increase in poor medical waste management and unsafe disposal [11].

Waste management depends on (i) the disposal facilities; (ii) monitoring; (iii) collection; (iv) transportation and (v) treatment, but also on (vi) the behavior and capacity of human resources [28].

A sustainable supply chain model that allows problems to be addressed must be considered at the same time as reducing environmental damage [29].

2.3. Hybrid Simulation

Simulation allows for the better planning of operations through knowledge and more precise information about the system, making it possible to improve or maintain the competitiveness of companies [30]. By using simulation, it is possible to improve the quality of decision-making in an easier and faster way [16].

Computer simulation has been used as a way of evaluating complex system designs to determine whether they meet specific operational objectives, determining which is best for making the most appropriate decisions, thus saving time and resources [31]. Computer simulation modeling is a useful tool in various situations, such as modeling more complex systems and communicating ideas and validating analytical models [32].

In order to study the problem from various perspectives, hybrid simulation allows for a better understanding of more complex systems, with multiple objectives, levels of aggregation and behaviors [33]. The concept of “hybrid simulation” is not consensual, in that it can encompass models that are implemented simultaneously on analogue and digital computers, models that have continuous and discrete variables, but also models that combine simulation with an analytical method such as optimization [34].

2.4. Hospital Supply Chain in the Context of Industry 4.0

The health sector has existed since the dawn of civilization and with the increase in the number of people and technological facilities, it is crucial to provide the health service with better facilities and flexibility through Healthcare 4.0, which has developed from Industry 4.0 [35].

Technologies related to Industry 4.0 such as the Internet of Things (IoT), Big Data Analytics and Cloud Computing have contributed to the advancement of technology related to the health sector [36]. Digital technologies in the healthcare sector can attenuate or even eliminate the high costs faced by healthcare systems, which account for 10% of gross domestic product in the European Union and 18% in the United States [37].

Due to the large amount of data in the health sector, the use of Big Data can improve the quality of the health service, since the quality of the health service depends on the volume, quality and correct interpretation of patient data [36]. The Internet of Things enables remote monitoring that facilitates the sending and receiving of information between patients and healthcare facilities, and is therefore a key element of Healthcare 4.0, leading to remarkable changes in the healthcare sector [38]. The Internet of Things plays a significant role in the collection and monitoring of data [39].

Other technologies used in Industry 4.0 include artificial intelligence, which is capable of detecting any problems a patient may have through the use of sensors in an emergency situation, which is proving to be a beneficial contribution to the health sector
Artificial intelligence is responsible for analyzing large amounts of data and making decisions based on learning from the data being analyzed [39].

3. Materials and Methods

The main objective of this work is to systematically analyze the literature on hybrid simulation in hospital waste supply chains in the context of Industry 4.0. A systematic literature review is a process that allows the collection of scientific publications on a given topic that can answer the research questions posed and that fit certain selection criteria [40]. Bibliometric analysis is a methodology that explores and analyzes substantial amounts of scientific data and whose importance has increased in recent years due to the advancement and availability of bibliometric software, as well as the interaction between different areas of bibliometric methodology [41].

The guidelines for performing a systematic literature review, namely PRISMA 2020, were therefore implemented as a methodology. The knowledge of the PRISMA 2020 statement is important when it comes to planning reviews so that as much information as possible is available [42].

This systematic literature review is designed to answer two research questions:

RQ1. What are the main difficulties in hospital waste supply chains?
RQ2. What contribution does simulation/hybrid simulation make to hospital waste supply chains?

Figure 1 provides an illustration of the methodology used throughout this research, which has allowed the above-mentioned research questions to be clarified.

![Research methodology](image)

**Figure 1.** Research methodology.

### Study Search

This systematic literature review used two databases, specifically SCOPUS and ScienceDirect, in order to collect as many articles as possible related to these concepts. The search was conducted on May 6, 2024. The following keywords were used to search for articles in the two databases in the “Title, abstract or author-specified keywords” search field: (“medical waste supply chain” OR “healthcare waste supply chain” OR “medical waste” OR “healthcare waste”) AND (“simulation” OR “Industry 4.0”). Through these conditions, 108 articles were found.

Table 1 presents the number of documents in the two databases under analysis.

<table>
<thead>
<tr>
<th></th>
<th>Scopus</th>
<th>ScienceDirect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of documents identified in the databases</td>
<td>97</td>
<td>21</td>
</tr>
</tbody>
</table>
Based on the results, it appears that the database with the most articles related to the subject of this systematic literature search is the Scopus database.

The inclusion criteria used in this paper were as follows: all existing documents since 2010. Then, duplicate articles were removed; (i) articles not written in English and (ii) only vaguely related to the theme were the exclusion criteria chosen for this research.

Table 2 summarizes the inclusion and exclusion criteria used for the document search.

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
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<tbody>
<tr>
<td>All documents dated since 2010</td>
<td>Non-English; vaguely related to the theme</td>
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</table>

The database search with these criteria resulted in 118 articles (97 in Scopus and 21 in ScienceDirect). Then, 15 repeated publications were removed, resulting in 103 documents. This was followed by the removal of six non-English documents and 77 other articles that were not suitable for the purpose of this research. The final result of the search was 20 articles since 2010. Figure 2 summarizes the results and the number of publications at each phase.

![Figure 2. Prisma 2020 flowchart.](image)

4. Results

The inclusion and exclusion criteria led to the selection of 20 documents. In this section, the documents will be analyzed from various aspects, such as the number of publications per year, the type of document, the number of publications per journal, the country or territory from which the document originated, the themes per document and the occurrence of keywords. Table 3 provides a summary of the general information about the selected documents.
<table>
<thead>
<tr>
<th>Title</th>
<th>Year</th>
<th>Main Objective, Methodology and Results</th>
<th>No of Citations (Scopus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimizing Waste Management Collaboration Processes Using Hybrid Modelling [43]</td>
<td>2024</td>
<td>This work proposes hybrid modeling with integrated discrete-event simulation, agent-based simulation and improved MCDC methods in order to optimize the number of workers with the minimum asynchronous waiting time and cost based on waste management process data. The results indicate that hybrid modeling can minimize 74% of the minimum asynchronous waiting time and 31% of the activity cost compared to the actual model under an overload condition.</td>
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<tr>
<td>Research on transportation management model of COVID-19 medical waste: a case study in Beijing, China [44]</td>
<td>2023</td>
<td>This article implements a transport route optimization model using Anylogic simulation software in the regional distribution of 118 tertiary hospitals and two large medical waste disposal plants in Beijing. This study enabled the analysis of two modes of hospital waste transportation (the most costly route and the fastest speed), contributing to the better management of hospital waste transportation.</td>
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<tr>
<td>Discrete cuckoo search algorithm in scheduling dynamic route of medical and non-medical waste transportation at regional-based health facilities during the COVID-19 pandemic [45]</td>
<td>2023</td>
<td>This work designs waste transport routes in such a way as to minimize the costs and distance using the Discrete Cuckoo Search algorithm. In this paper, a clustering process was carried out and then the algorithm was implemented. Finally, a comparison was made with other algorithms. The results reveal that the Discrete Cuckoo search algorithm had better results than the Artificial Bee Colony (ABC) and Particle Swarm Optimization (PSO).</td>
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<tr>
<td>Designing reverse logistics network for healthcare waste management considering epidemic disruptions under uncertainty [46]</td>
<td>2023</td>
<td>The main aim of this study was to create a reverse logistics network to manage healthcare waste. The model minimizes the total cost and the risk to the population. A simulation algorithm using probabilistic distribution functions was implemented in order to generate data of different sizes and to evaluate the proposed model.</td>
<td>3</td>
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<tr>
<td>Conceptual design and simulation study of an autonomous indoor medical waste collection robot [47]</td>
<td>2023</td>
<td>The purpose of this article was to describe a project for a mobile robot whose tasks consist of intelligently identifying and collecting a group of hospital wastes. To achieve this, several simulations were created using the Robot Operating System and the Gazebo simulator. A LIDAR sensor was also implemented to monitor the robot’s surroundings and enable autonomous navigation.</td>
<td>1</td>
</tr>
<tr>
<td>The Influence of Pandemic COVID-19 on Hazardous Waste Management from Hospital A in Yogyakarta [48]</td>
<td>2023</td>
<td>The main objective of this study was to analyze the management of hazardous waste during the pandemic in a hospital in Yogyakarta. For this purpose, dynamic systems modeling was used for the technical, financial and environmental aspects using Vensim PLE with a stock–flow diagram.</td>
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<tr>
<td>Title</td>
<td>Year</td>
<td>Abstract</td>
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<tr>
<td>Dynamic system modeling applications were used, considering technical, financial and environmental aspects, using Vensim PLE with the stock–flow diagram. The results showed that there was an increase in the production and transportation of waste during the pandemic, reaching 9.36%. In total, 11,756 kg/year of waste was produced and the waste transportation costs increased to IDR 109,860,000/year.</td>
<td>2022</td>
<td>This work investigated a method of effectively guiding the green transformation of medical waste concerning the economic interests of medical institutions and manufacturers of masks. In this paper, a dynamic system model was implemented for the simulation analysis.</td>
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<tr>
<td>Green Transformation of Anti-Epidemic Supplies in the Post-Pandemic Era: An Evolutionary Approach [49]</td>
<td>2022</td>
<td>The main purpose of this work was to determine the number of medical resources in different proportions of time and cost in an attempt to identify the relationship between cost, time and the number of workers involved in the waste management system of a hospital in East Java in Indonesia, through a combination of Discrete Event Simulation and MOORA. The results showed that less incoming waste requires fewer workers than in situations with more waste.</td>
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<tr>
<td>Optimizing Time and Cost Activity based on Discrete Event Simulation with Multi-Objective Optimization Method by Ratio Analysis (MOORA) [50]</td>
<td>2022</td>
<td>This article analyzes the principles of green governance and highlights the problems that exist in the healthcare waste management system in Wuhan. The work proposes a hybrid model combining the Genetic Algorithm (GA) and Ant Colony Algorithm (ACO) to achieve hospital waste transportation optimization. Finally, this article analyzes the role of government, hospitals and communities in the process of disposing of healthcare waste and suggests guidelines for its disposal.</td>
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<tr>
<td>Research on optimization of healthcare waste management system based on green governance principle in the COVID-19 pandemic [51]</td>
<td>2021</td>
<td>The main goal of this study was to evaluate different levels of segregation in household waste mixed with hospital waste in the Thrace Region of Turkey. Therefore, the Stella and Vensim Simulation was implemented to evaluate medical waste flows. The results indicated a predicted increase from almost 2000 tons/year to almost 3000 tons/year in 2045. There is also the possibility of avoiding 300 tons of hospital waste per year by reducing the domestic content of hospital waste to 50%.</td>
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<tr>
<td>A comprehensive waste management simulation model for the assessment of waste segregation in the health sector [52]</td>
<td>2021</td>
<td>This work explores the problem of collecting medical waste in the city of Barcelona, minimizing the total time invested by the fleet of vehicles to complete the task. Thus, the combination of multi-start biased–randomized heuristics (BRHs) with Monte Carlo Simulation allows more effective results in situations where the travel and collection time are uncertain.</td>
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<tr>
<td>Waste Collection of Medical Items under Uncertainty Using Internet of Things and City Open Data Repositories: A Simheuristic Approach Open Access [53]</td>
<td>2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Title</td>
<td>Year</td>
<td>Description</td>
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</tr>
<tr>
<td>Managing Medical Waste during COVID-19 Outbreak: A Simulation Approach [54]</td>
<td>2021</td>
<td>The aims of this study were to explore the strategies and policies needed to manage the amount of medical waste in Indonesia in two situations: during an outbreak such as COVID-19 and under normal conditions (no outbreak). Systems Dynamics is used in this study and helps to optimize the medical waste management system during COVID-19.</td>
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<tr>
<td>The design of medical waste treatment in public health center (MWT-P) for reducing total bacteria count in Banjarbaru [55]</td>
<td>2020</td>
<td>This study explores variations (contact time and chlorine dose variation) in the different stages of hospital waste processing in the Public Health Center of the city of Banjarbaru. This study was conducted by simulating variations. The study results indicated that the use of MWT-P decreases the number of microorganisms or bacteria in medical waste.</td>
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<tr>
<td>Adaptive protocol generation for group collaborative in smart medical waste transportation [56]</td>
<td>2020</td>
<td>This work deals with the challenge of collective decision-making between intelligent components in the transportation of medical waste by using Automated Guided Vehicle Medical Waste Transportation (AGV-MWT).</td>
<td></td>
</tr>
<tr>
<td>Path optimization of medical waste transport routes in the emergent public health event of COVID-19: A hybrid optimization algorithm based on the immune-ant colony algorithm [57]</td>
<td>2020</td>
<td>This article applies an immunological algorithm to establish a model for locating urban medical waste storage sites in Wuhan, China. In this work, various temporary storage points are analyzed according to the environmental impacts and evaluation criteria, using the Q-value method to allocate hospital waste vehicles and applying the immune ant colony algorithm along with the tabu search algorithm.</td>
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<tr>
<td>The use of discrete event simulation for optimal performance of blood banks (A case study of Al-Shifa Central Blood Bank) [58]</td>
<td>2020</td>
<td>The aim of this study was to satisfy the need for blood while minimizing the phenomenon of outdated blood units. Discrete Event Simulation was implemented to represent the Al-Shifa Central Blood Bank in order to enable better decision-making by analyzing the system’s behavior.</td>
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<tr>
<td>Solving a routing problem of collect infectious healthcare waste with stochastic demand: Case of Sfax governorate in Tunisia [59]</td>
<td>2020</td>
<td>This work analyzes approaches that help municipalities make decisions on how to implement an appropriate system for transporting infectious healthcare waste. Two approaches were proposed: (1) a combination of the exact method with Monte Carlo simulation, and (2) a combination of the same simulation tools with those proposed by Clarke and Wright (C&amp;W); this made it possible to support decision-making in the creation of a transport system for infectious medical waste.</td>
<td></td>
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<tr>
<td>An optimization model for collection, haul, transfer, treatment and disposal of infectious medical waste: Application to a Greek region [60]</td>
<td>2017</td>
<td>This paper presents an optimization model that minimizes the cost of a system for collecting, transporting, transferring, treating and disposing of infectious hospital waste (optimal location of treatment facilities and transfer stations, their design capacities (t/d), the number and capacity of all waste collection sites, and transportation and transfer vehicles and their optimal transportation route).</td>
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</tr>
</tbody>
</table>
A system dynamics approach for hospital waste management in a city in a developing country: the case of Nablus, Palestine [61]

This study focuses on the development of a system dynamics simulation model for use as a predictive tool in hospital waste management for better decision-making. Through this model, it is possible to analyze different future scenarios of hospital waste situations in Palestine. The model developed allows for a comparison of the total amount of waste produced between different hospitals and to predict the generation of more waste, as well as treatment costs.

Scenario for a simulation of health services’ waste: A methodological study [62]

This methodological study aims to validate the different contents of a scenario to be used in the form of a healthcare waste management simulation. Based on the scenario implemented and improved by experts and students, it will be possible to train healthcare professionals in different contexts.

4.1. Publications by Year

The number of publications in general has increased in recent years, with the highest number of articles published in 2020 and 2023 (both with 5 articles). It should also be noted that there were no articles published on this topic in 2019. Figure 3 illustrates the evolution of the number of articles published per year on the subject.

Figure 3. Documents by year.

Figure 3 indicates that the number of articles published on this subject could increase even further. There is also a difference in the publication figures between the years 2016 and 2017 and the years from 2020 onwards.
4.2. Documents by Type

Following this, the types of document obtained were analyzed. Of the 20 documents, 30% were conference documents, while the remaining 70% were articles. This is analyzed in Figure 4.

![Documents by type](image)

**Figure 4.** Documents by type.

4.3. Journals

With regard to the journal in which the studies were published, the *International Journal of Environmental Research and Public Health* had the highest number of publications (three publications). The remaining journals had one publication. Figure 5 below presents the number of articles per journal.

![No. of Articles](image)

**Figure 5.** Number of articles by source.

4.4. Documents by Country or Territory

China and Indonesia are the countries that have conducted the most studies on the subject of the article, with five documents each. The United Kingdom and Palestine are next, with two documents each. Figure 6 displays the number of documents per top 10 country/territory. Figure 7 illustrates the density of the countries that contribute most to publications on this topic using VOS viewer software. It should be noted that the higher the density of countries, the more publications there will be.
4.5. Documents by Subject Area

Figure 8 provides a summary of the number of documents per area of work. It should be emphasized that only topics with more than one document were selected for this analysis. It should be emphasized that around 33% of the documents are in the field of environmental science and 22% are in computer science.
4.6. Keywords Analysis

The analysis of key words is important as it makes it possible to identify the main topics of each publication. Figure 9 presents the occurrence of key words using the WordArt software. Due to the substantial number of keywords, only those with more than two occurrences were analyzed. It should be mentioned that the larger the keywords, the greater the number of occurrences in the publications under analysis. Figure 9 shows that concepts such as COVID-19, Medical Waste and Hospital Waste are those with the most occurrences.

Figure 9. Keyword occurrence.

Figure 10 and Table 4 display the keyword co-occurrence network, with eight clusters identified (eight different colors). The words in orange belong to the seventh cluster, which includes the following words: nursing; simulation training and validation studies. Figure 11 gives a visualization of the density of the keywords.
Figure 10. Keywords Co-occurrence network visualization.

Table 4. Cluster from keywords.

<table>
<thead>
<tr>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>COVID-19; Environmentally friendly masks; Evolutionary game; Government regulation; Green Transformation; Simulation; Waste generation</td>
<td>Developing countries; Generation rate; Hospitals; Palestine; System Dynamics</td>
<td>Domestic waste; Hazardous waste; Medical waste flows; Simulation modeling; System parameters</td>
<td>Ant colony algorithm; Immune tabu search algorithm; Path Optimization; Transit storage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cluster 5</th>
<th>Cluster 6</th>
<th>Cluster 7</th>
<th>Cluster 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastest speed; Shortest path; Tertiary hospital; Transportation</td>
<td>Dynamic modelling; Generation; Pandemic</td>
<td>Nursing; Simulation training; Validation studies</td>
<td>Bacteria; Medical waste; Treatment plan</td>
</tr>
</tbody>
</table>

Figure 11. Keywords Density Visualization.
5. Discussion

5.1. Generation Rate of Medical Waste

Hospitals, medical centers, laboratories, veterinary clinics, research centers, morgues, blood banks and nursing homes are the biggest sources of medical waste [63]. Only 15% of all medical waste is considered “hazardous waste”, which is infectious or toxic [12]. Developed countries are responsible for almost 11 kg of hazardous waste per hospital bed per day (kg/bed/day), while developing countries are responsible for 6 kg [64]. The volume of waste depends on various factors such as [65] the waste management technique, the type of healthcare institution, the amount of reusable equipment available and the number of patients treated each day.

Table 5 provides a list of some countries’ positions in the health system performance ranking and Figure 12 gives an analysis of the total production of medical waste in these countries.

Table 5. WHO ranking of health system performance (Adapted from [20]).

<table>
<thead>
<tr>
<th>Country</th>
<th>WHO Ranking of Health System Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>11</td>
</tr>
<tr>
<td>United States</td>
<td>37</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>18</td>
</tr>
<tr>
<td>France</td>
<td>1</td>
</tr>
<tr>
<td>Spain</td>
<td>7</td>
</tr>
<tr>
<td>Brazil</td>
<td>125</td>
</tr>
<tr>
<td>Turkey</td>
<td>70</td>
</tr>
<tr>
<td>Jordan</td>
<td>83</td>
</tr>
<tr>
<td>Pakistan</td>
<td>122</td>
</tr>
<tr>
<td>Tanzania</td>
<td>156</td>
</tr>
</tbody>
</table>

A detailed analysis of Table 5 demonstrates that France and Spain have the best ranking in relation to the other countries under analysis, being in the top 10, while countries such as Brazil and Tanzania have the worst positions in this analysis (they are not in the top 100).

Figure 12. Total healthcare waste generation (kg/bed-day) (Adapted from [20]).
Figure 12 also shows that the country with the highest production of medical waste is the United States, with 10.7 kg/bed-day, while the lowest value is found in Tanzania, with only 0.14 kg/bed-day.

After an analysis, it can be seen that there is no relationship between the position in the health performance ranking and the total amount of medical waste generated by each country. The position of the United States (37th), with the highest amount of medical waste at 10.7 kg/bed-day generated, compared to the position of Tanzania (156th), with only 0.14, is worth noting.

5.2. Impact of COVID-19 Pandemic on Medical Waste Management and Environment

During the COVID-19 pandemic, the use of disposable safety equipment such as gloves, surgical masks and air purifiers rose abruptly and unexpectedly in order to stop the virus, therefore increasing the amount of hazardous medical waste [66]. The COVID-19 pandemic has led to an increase in medical waste around the world and a reduction in the capacity of healthcare professionals to manage it [67]. Good waste management through proper handling and use helps to reduce the negative effects on public health and the environment [5]. The COVID-19 pandemic has led to a significant increase in the generation and composition of municipal solid waste, reaching 2.5 million tons per month [28].

Sustainable medical waste management is a challenging issue, especially in emergency situations such as the COVID-19 pandemic [68]. Despite its adverse socio-economic impact, COVID-19 made it possible to reduce the level of environmental pollution by up to 30%, since, for example, air travel was reduced by 96%, and the emissions from factories were reduced [6].

5.3. Implications of Medical Waste for the Environment and Public Health

Pollution is seen as the biggest environmental problem, causing illness and premature death all over the world, with the health sector being a main contributor to acid rain, greenhouse gas emissions and the destruction of the atmosphere’s ozone layer [1]. It is estimated that hospitals and other healthcare facilities are some of the main contributors to environmental pollution, accounting for 4.4% of greenhouse gas emissions [69].

The incorrect management of hospital waste can lead to patients, healthcare professionals and waste managers being exposed to injuries, infections, toxic effects and air pollution [68]. Medical waste management is a task that puts human health and life at risk, especially in developing countries [64]. The poor management of waste produced by healthcare institutions can cause health concerns and create a negative impact on the ecosystem, affecting plants and animals [70].

The disposal of medical waste in uncontrolled areas leads to soil and groundwater contamination, directly affecting the environment [71]. The World Health Organization (WHO) stated in 2018 that, due to the use of infected syringes, there has been a spread of infectious diseases, with 21 million people developing hepatitis B, 2 million developing hepatitis C and 0.26 million developing HIV [69].

5.4. Medical Waste Management Process

The medical waste management process aims to minimize risks and control epidemic infections, and includes the processes of (i) collection, (ii) separation, (iii) storage, (iv) transportation, (v) processing and, finally, (vi) disposal [5]. Medical waste management is a series of steps starting from the generation of medical waste to safe disposal [72].

At the collection stage, medical waste is removed from healthcare institutions [73]. The main objective of transportation planning for medical waste is to produce as little pollution as possible from the collection site to the disposal centers [74].

The collection and transportation time, the length of the road, the transportation capacity and vehicle planning, and the type of disposal all play an essential role in more
effective medical waste management [75]. The waste separation stage is a key step in the management process, since a mixture of infectious and non-infectious waste can lead to a total mixture of infectious waste, thus increasing disposal costs and exposing healthcare professionals to higher risks [76].

An increase in hospital waste implies major challenges for its treatment, for which there are various methods, such as microwaving, autoclaving and thermal treatment and disposal [77].

5.5. Research Questions

This systematic literature review is designed to answer two research questions. In this section, the research questions will be analyzed.

RQ1. What are the main difficulties in hospital waste supply chains?

The increased demand for more medical care has led to the greater production of medical waste. Much of it has to be treated differently from the other types due to its ability to transmit diseases. Hospital waste supply chains therefore need to respond effectively and efficiently to the large quantities of medical waste created by hospitals, health centers and research laboratories.

The proper transportation and treatment of medical waste is also a difficulty for supply chains due to its ability to transmit diseases and its negative impact on the environment.

RQ2. What contribution does simulation/hybrid simulation make to hospital waste supply chains?

Simulation is a tool that allows you to analyze different scenarios to see which is best for each decision-making process. It improves the performance of both medical waste transportation and treatment processes. One of the fundamental contributions of simulation is that it makes it possible to assess the behavior of a given system without directly affecting it, since these tests are carried out on computer models. With the constant increase in the complexity of systems, combining two or more simulation methods (hybrid simulation) allows for more precise and effective solutions than would be possible using just one simulation method.

6. Conclusions and Limitations

This work consisted of a systematic literature review of each concept central to the study: industry 4.0, simulation and the hospital waste supply chain. After this, discussion topics linked to the main theme were added.

The importance of the health sector has increased as the world’s population has grown. Everyone needs healthcare, which means that medical waste is being generated more and more. Since this waste can be infectious, greater care must be taken in its treatment and disposal.

Therefore, improving the performance of a hospital waste supply chain is the main focus of every manager in order to increase or maintain competitiveness and respond to people’s needs. The poor management of this waste can lead to harmful impacts on the environment, but also on living beings.

One of the tools that many supply chains have been using is simulation, one of the pillars of Industry 4.0, which allows complex systems to be modelled in order to study them and analyze the best scenario for more appropriate decision-making, while minimizing costs.

Simulation makes it possible to analyze various scenarios in a supply chain, allowing for better decision-making. The management of medical waste has stages, from its collection in healthcare institutions to its disposal.

In order to improve the performance of a given medical waste supply chain, different scenarios must be carried out to determine which is best, and simulation can make the medical waste supply chain more efficient.
The results indicate that the years 2020 and 2023 had the highest number of publications (with five each) and that countries such as China and Indonesia had the highest number of documents on this topic (with five each). The topics in this research area with more related documents were environmental sciences, computer sciences and medicine.

The study concluded that the amount of medical waste generated does not depend on the ranking of the health system’s performance, but rather on the difference between developed and developing countries.

In this systematic literature search, the PRISMA 2020 guidelines were used to select the appropriate publications for the topic. However, there is always the possibility that during this selection process, certain documents that are also important to the topic are not selected. Another limitation was the existence of various terminologies for one concept, which may have led to a search with fewer results than that using a particular terminology.

In conclusion, this study shows that simulation methods can be used to increase the performance of medical waste supply chains. In order to explore the subject further and reduce the existing gaps in simulation/hybrid simulation as a decision support tool for improving the performance of hospital waste supply chains, the following should be addressed in future research:

(i) What the economic impact is in situations of good medical waste management;
(ii) The existence of more practical cases in which simulation has been used as a tool for improving the performance of supply chains and the economic results and comparison of the situation before and after using simulation;
(iii) The environmental impacts caused by medical waste and what hybrid simulation can do to improve sustainability.


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References


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