sustainability

Article

Sustainable Inventory Management in Supply Chains: Trends and Further Research

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Abstract: This article presents an overview of the models applied to sustainable inventory management in supply chains and a roadmap for new research. It aims to address the lack of understanding of how sustainability is being incorporated into quantitative inventory management models in the supply chain context. The study is based on a classification of the reviewed literature according to the following criteria: supply chain structure, environmental approach, problem type, modeling, and solution approach. As a result, 36 articles were analyzed and classified. The main findings show that studies that incorporate social sustainability into inventory management along supply chains are lacking, while environmental studies are a growing research area. Uncertainty issues also need to be incorporated into sustainable inventory management models. Another important result of this study is the definition of a roadmap with trends and future research guidelines. The identified future research guidelines include incorporating decisions that can help to improve economic, environmental, and social sustainability. Thus, future studies should focus on both following quantitative models that incorporate inventory decisions integrally with transportation and location decisions, and more complex models, and employing new algorithms and heuristics to solve them.

Keywords: inventory management; sustainability; supply chain

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1. Introduction

The economic growth process based on process technology began after the first industrial revolution in the second half of the 18th century. The industrial revolution unleashed not only an economic, scientific, and technical boom but also an intensive, extensive and irrational use of natural resources to search for accelerated economic growth models that occurred when it began. Environmental aspects are very important for reducing the global warming effect associated with increasing CO_2 emission rates as a result of globalized industrialization, goods storage, and transportation. According to Arikan et al. [1], the storage and transport of goods are considered the most important causes of environmental hazards in the logistics chain and are the main reasons for CO_2 emissions.

Sustainable inventory management (SIM) relates to decisions on inventory, warehousing, and material handling by focusing on reducing environmental and social impacts without affecting profitability [2]. Incorporating location and transportation issues into modeling could lead to sustainable supply chains (SCs). Recent research has highlighted the need to include factors other than traditional inventory models to design sustainable inventory systems by integrating the factors affecting the environmental impact into the traditional economic order quantity (EOQ) model [3]. It is crucial to develop a SIM model that takes into account income increase and waste prevention and reduces energy costs [4]. Decisions on lead times, replenishment quantities, and storage facilities influence emissions and costs [5].

Very few review articles have focused on the collection and analysis of inventory models that include sustainability, which is the main motivation of this paper. Pattnaik et al. [6]

present a systematic literature review about integrating sustainability issues into inventory management models, specifically those topics that consider environmental criteria such as greenhouse gas (GHG) emissions, ecological quality controls, unsold inventory, and fixed carbon costs. Hence these authors mainly contribute decision-makers to identify the environmental and social factors that could be included in inventory models to encourage sustainable development. A comprehensive literature review of studies on inventory routing problems that incorporate sustainability aspects is provided by Malladi and Sowlati [7]. Chan et al. [8] classify the mathematical problems that deal with the management of sustainable manufacturing systems by classifying selected articles into three categories according to the main manufacturing system elements: production planning and control; inventory management and control; and manufacturing network design. Finally, a more extensive review that focuses on green SC quantitative models for SIM is found in Becerra et al. [9]. They identify and classify specific criteria related to modeling sustainable inventory problems in terms of purpose, application context, SC structure, decision level, shared information, inventory policies, inventory modeling, sustainability, circular economy and green modeling approaches, modeling approach, solution approaches, and software tools. Yadav et al. [10] identify the research gaps and advantages of waste management, preservation technology, and setup cost reduction from an SC perspective with a smart manufacturing system for products with cross-price elasticity of demand.

In addition, the present study attempts to bridge the research gap of how sustainability should be integrated into quantitative SC inventory management models. Therefore, this article contributes to identifying research trends related to quantitative SIM models in SCs and, by doing so, to proposing a roadmap for future studies. These trends and further research works are based on the following classification criteria: environmental approach, problem type, SC structure, model approach, and solution approach. The literature review by [6] focuses on SIM models approached by quantitative methods (the modeling and solution approach) exclusively and in a supply-chain context by also considering the inventory problem, location, and routing problems.

Therefore, the aim of this study is twofold: (1) to offer an overview of the literature on SIM in SCs from an environmental perspective by identifying the type of problem, SC structure, model, and solution approach; (2) to propose a roadmap for future research lines based on the trends identified in this work according to the classification criteria. The posed research question is: what is the roadmap of trends and further research lines for SIM models in an SC?

The remainder of the paper is structured as follows. Section 2 describes the review methodology. Section 3 offers an overview of the literature on SIM in SCs. Section 4 presents the discussion and proposes a roadmap for further research. Finally, Section 5 includes the conclusions and further research from the study.

2. Review Methodology

In order to fulfill this overview objective, relevant literature was compiled after considering the scientific articles published in the journals indexed in Scopus and Web of Science (WoS). In order to answer the research question, the following keywords were used in combination: supply chain, supply network, sustainable, green, circular economy, environment, social, inventory management, quantitative method, mathematical programming, optimization, analytic models, simulation, and artificial intelligence. No time window is defined. According to these search criteria, WoS and Scopus, respectively, indicated 142 and 183 related scientific articles published from 2004 to 2021. These articles were selected based mainly on the defined exclusion criteria: papers not related to the principal research field, i.e., that do not include environmental aspects, case studies on specific sectors not related to SCs, nonquantitative models, among others; duplicated studies; conference reviews; articles that neither present potential future lines nor develop a model (see Table 1). The remaining 36 articles were analyzed and classified to learn trends and future research areas. The followed review methodology is found in Figure 1.

Table 1. Search methodology and paper selection process.

Keyword Used	(Supply Chain or Supply Network) and (Sustainab* or Green or Circular Economy or Environment or Social) and (Inventory Management) and (Quantitative Method or Mathematical Programming or Optimization or Analytic Models or Simulation or Artificial Intelligence)
Scopus database	183 articles
Wos database	142 articles
Total papers in the two databases excluding duplication, conference reviews, not considering environmental aspects, case studies on specific sectors not related to SCs or nonquantitative models	47 articles
Articles that present potential future lines or develop a quantitative model	36 articles

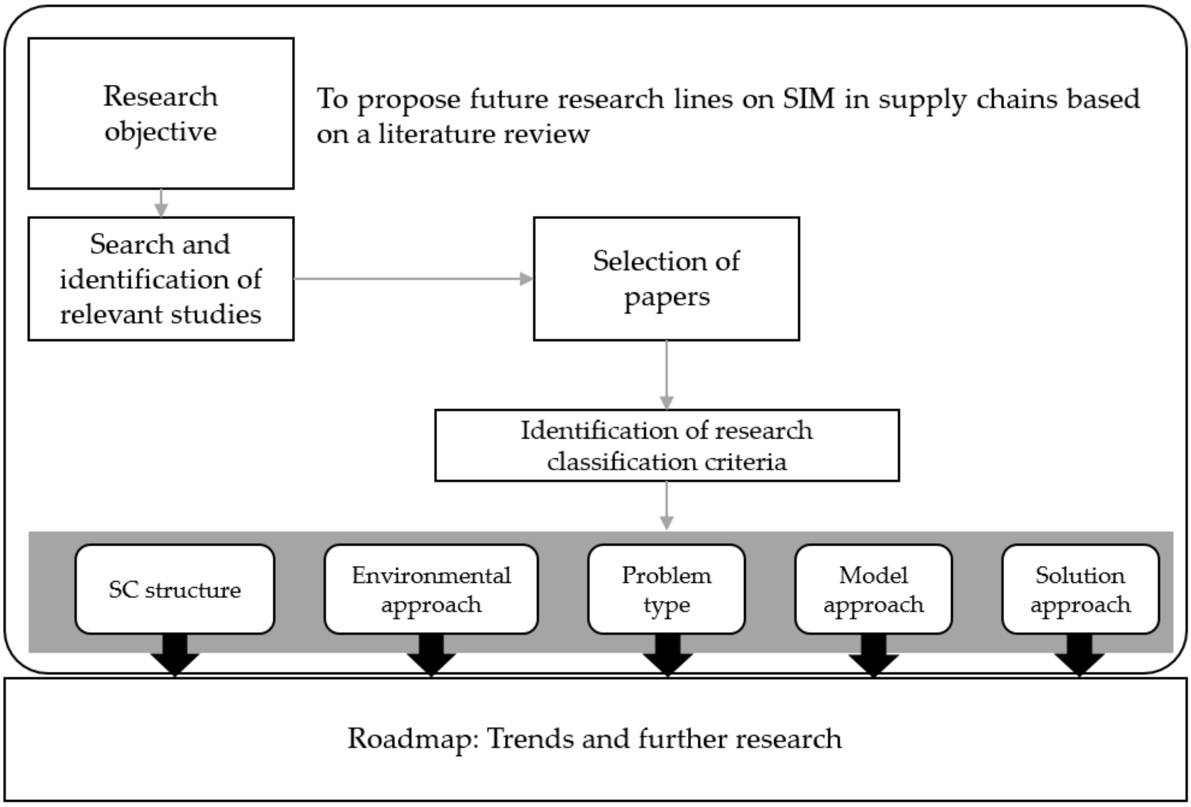

Figure 1. Review methodology.

Of the 36 selected papers, 25% of the articles about SIM in SCs are published in three journals: *International Journal of Production Economics*, *Computer Aided Chemical Engineering*, and *Journal of Cleaner Production*. Appendix A.1. Distribution of Reviewed Publications per Journal presents the distribution of the reviewed publications per journal.

The number of publications per year (see Figure 2) reveals that researchers have recently paid attention to this research topic. Most of the research (86.11%) has been conducted in the last 10 years, and over half the research papers (61.11%) were published in the past 5 years.

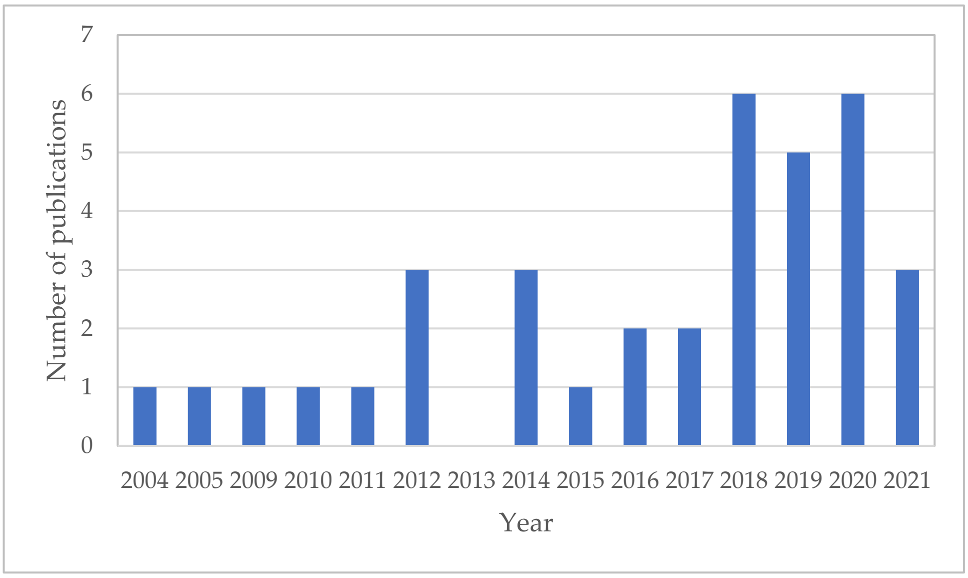

Figure 2. Number of publications per year.

3. Literature Review

The literature review focuses mostly on the main objective of the reviewed articles, and on the proposals of future research lines, by distinguishing the three sustainability aspects: economic (EC), environmental (EN), and social (S). The research methodologies addressed in the reviewed papers are classified according to (Dangayach and Deshmukh [11] and Malhotra and Grover [12]): (i) conceptual, basic or fundamental concepts; (ii) descriptive, an explanation or description and questions related to the addressed problem; (iii) empirical, where the study data are taken from existing databases, and from literature reviews, case studies and taxonomy or typology approaches; (iv) cross-sectional exploratory, with surveys at a given time; (v) longitudinal exploratory, also based on surveys in which data are collected at two different time points, or more, in the same organizations. Here, empirical proposals stand out; that is, those referring to mathematical programming and simulation models. Very few studies include a statistical analysis by exploratory cross-sectional research, and only two studies select the proposed conceptual research, specifically by literature reviews. The details of the findings of this literature review are provided in Appendix A.2. Sustainability Aspects, Research Methodology, Objectives and Proposed Further Research per Article.

Table 2 presents an overview of how SIM in SCs has been studied. It includes the following classification criteria: SC structure: D (dyadic), SE (serial), C (convergent), DV (divergent), CJ (cojoined), N (network), CL (closed-loop), RL (reverse logistic); environmental approach: R1 (recycling), R2 (reusing), R3 (remanufacturing), R4 (renewable), R5 (repair), R6 (reduce); problem type: L (location), I (inventory), R (routing); model approach: MP (mathematical programming), S (simulation), R (regression), C (conceptual); solution approach: E (exact), H (heuristic), M (metaheuristic), ST (statistical) and SS (simulation software).

The SC structures proposed by [13] are extended in this work to include reverse logistics and closed-loop approaches because both correspond to 30% of the reviewed articles. These structures include product returns, which imply reusing, repairing, reconditioning, remanufacturing, and recycling materials, an efficacious reverse logistics network design that offers not only environmental benefits but also economic benefits in terms of reduced raw material acquisition, inventory management, and waste disposal [14].

When developing inventory models to consider sustainability by incorporating its three pillars, the S aspect appears to be poorly studied because only nine of the reviewed articles incorporate it. For example, Battini et al. [3] apply "external costs" to jointly include the EN and S dimensions in delivery operations, warehousing, and waste disposal.

Nativi et al. [15] propose a model that involves an S approach for patients to gain equitable access to essential medicines. Ivanov [16] and Ganev et al. [17] agree about using the offer of jobs in the local economy to estimate the S impact. Dekker et al. [18] developed a simulation model to study the effect of changing order size on the selected performance measures by addressing the S issue; for instance, it addressed the service level, amount of wasted food, and a product's average remaining life. By also taking social welfare as an objective in sustainability [19], Halat et al. [20] specifically develop a model to guarantee access to food and healthcare.

Table 2. Overview of SIM in SCs.

Reference	SC Structure	Environmental Approach	Problem Type	Model Approach	Solution Approach
Arikan et al. [1]	SE	R6	I	S	SS
Battini et al. [3]	N	R6	I	EOQ	H
Chen et al. [4]	CJ	R6	I	MP	M
Fichtinger et al. [5]	U	R6	I	S	SS
Ali et al. [14]	RL	R1, R2, R3	I	MP	E
Nativi and Lee [15]	RL	R1	I	R	ST
Ivanov [16]	N	R6	L	MP	E
Ganev et al. [17]	N	R4	L-I-R	MP	E
Dekker et al. [18]	D	R6	I-R	S-C	SS
Tsolakis and Srai [19]	U	R4	I	S	SS
Halat and Hafezalkotob [20]	CJ	R6	I	MP	E
Al-Haidous et al. [21]	N	R6	I-R	MP	M
Žic and Žic [22]	SE	R6	I	S	SS
Amer et al. [23]	N	R6	I-R	S	SS
Mohammadnazari and Ghannadpour [24]	C	R6	I-R	MP	E
Zhang et al. [25]	C	R6	L-I-R	MP	E
Sun et al. [26]	N	R6	L-I-R	MP	E
Ching et al. [27]	D	R6	I	S	SS
Paam et al. [28]	D	R6	I	MP	E
Wang et al. [29]	CJ	R6	I-R	MP	M
Nikolopoulou and Ierapetritou [30]	U	R1, R2, R3, R4, R6	L-I-R	MP-C	E-H
Bostel et al. [31]	RL	R1, R2, R3, R5	L-I-R	MP-S	E-H-SS
Kuo [32]	CL	R3	I	S	SS
Calmon and Graves [33]	CL	R3, R5	I	MP-S	M
Guo et al. [34]	CL	R2, R3	L-I	MP	M
Tighazoui et al. [35]	RL	R3	I-R	S	M
Ross et al. [36]	CL	R2	I	S-R	ST
Yang et al. [37]	CL	R2	I	MP	M
Zhang et al. [38]	C	R4	L-I-R	S	SS
Yılmaz Balaman and Selim [39]	CJ	R4	L-I-R	MP	E
Pati et al. [40]	RL	R1	I-R	MP	E
Ahmadini et al. [41]	SE	R6	I	MP	E-H
Rout et al. [42]	D	R6	I-R	MP	H
Tavana et al. [43]	N	R6	L-I-R	MP	E
Ugarte et al. [44]	D	R6	I-R	S	SS
Takeda et al. [45]	D	R6	I	S	SS

Environmental approaches have been widely studied. Here from the circular economy perspective, extending the options for value retention from the well-known reduce, reuse, and recycle policies to the 10R policies is suggested [46] by including the criteria proposed in this article. The most studied concept is "reduce" (R6) because it appears in 22 of the reviewed articles (see Figure 3) and is described to minimize GHG emissions [1,5,18,20–24,42–44,47] and to reduce waste production rather than disposing of created waste [3,4,25–30,45]. Ahmadini et al. [41] incorporate both GHG emissions and waste disposal minimization. Another studied environmental aspect is "remanufacture", which involves products at the end of their life or them needing maintenance and being returned. Parts or components are refurbished to be used as new products [14,30–35]. The "Reuse" (R2) aspect is less studied than the others. However, it comes over as a relevant aspect because it is often studied along with remanufacturing processes by considering return items that can be directly reused without them having to undergo major operations [14,30,31,34,36,37].

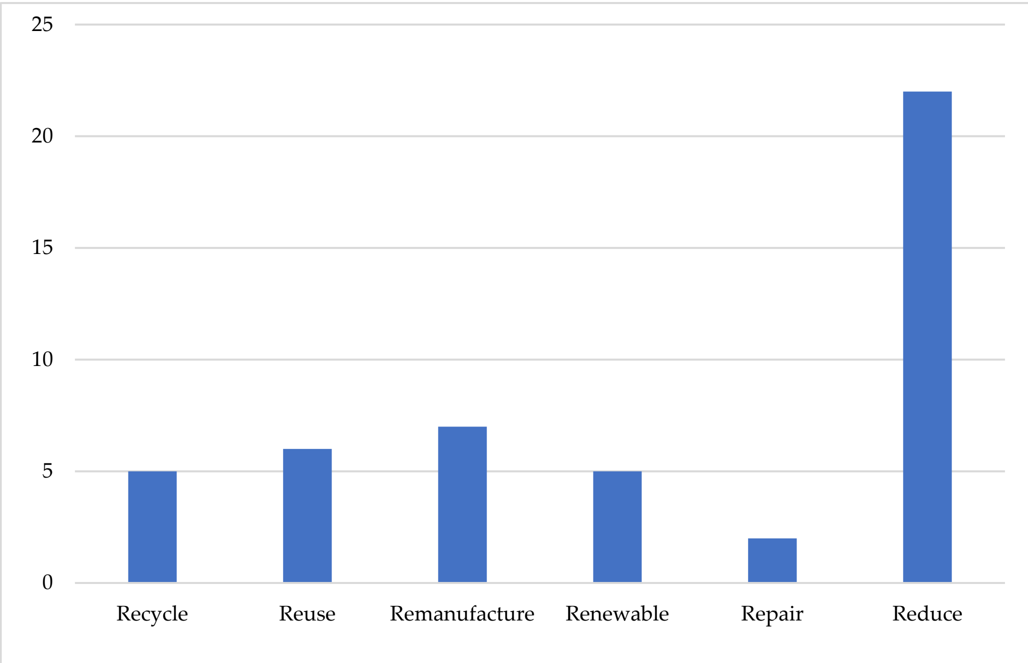

Figure 3. Number of publications per environmental approach.

The reviewed literature identified three problem types; location, inventory, and routing. They appear as individual problems or as combinations of two or three. Only one article includes the location problem in a review, that of Ivanov [16], who determines the optimum location of a bioethanol plant. In Guo et al. [24], an optimal solution to the location-inventory problem is developed to define the location and number of orders placed annually in a CL SC by considering sales on the primary and secondary markets for new and used products, respectively. Only one article presents a model that solves an inventory-production problem; Ahmadini et al. [41] consider that the production process contributes immensely to global warming. Eight articles solve the location-inventory-routing problem. This problem type addresses the relevance of coordinating location decisions, inventory management, and vehicle routing, such as selecting the distribution center's location, allocating customers for distribution, transportation routing of vehicles, and inventory strategy formulation [17,25,26,30,31,38,39,43].

Of all the available model approaches, mathematical programming models are the most widely used to solve the aforementioned problems (66.67%). Figure 4 particularly depicts: mixed-integer linear programming with six single objective cases [16,17,20,24,26,28]; multi-objective models [21,42]; multi-objective with fuzzy goal programming [39,43]; fuzzy multi-objective linear programming [14]; a multi-objective fractional programming model by Ahmadini et al. [41]; linear programming with one case [40]; sustainable EOQ developed by Battini et al. [3]; a constrained programming model overcome by Zhang et al. [25]; a stochastic optimization problem [33]; a Markov decision process [37]; mixed-integer nonlinear programming [34]; two integer programming models [4,29]. Simulation models are also widespread (33.33%). Bostel et al. [31] and Nikolopoulou et al. [30] examine both simulation and mathematical programming models. Simulation models offer two main approaches: discrete-event simulation [1,5,18,22,23,32,35,36,38,44,45] and system dynamics models [19,27]. Dekker et al. [18] and Nikolopoulou and Ierapetritou [30] apply a conceptual model to supplement their studies. Two regression models appear: one by Ross et al. [36] that describes a hybrid simulation-regression model and a regression model for the insight generation of managerial decisions by [15].

Figure 4. Distribution of publications per model and solution approach.

Solution approaches are closely related to the modeling approach. Thus, mathematical programming problems are solved by exact methods (58.33%), heuristics (16.67%), and metaheuristics (25%). Otherwise, simulation models are modeled and solved mostly by simulation software (91.67%). Tighazoui et al. [35] use metaheuristics to overcome their simulation problem. Ross et al. [36] and Nativi and Lee [15] apply a statistical approach to develop their multilinear regression models.

Finally, regarding the distribution of the articles reviewed in the different industrial sectors, 25% do not define a specific sector, but 22% focus on consumer goods, 14% on the energy sector, 8% on transport, and 8% on electrical and electronic devices. The rest are distributed in the different sectors, as shown in more detail in Figure 5.

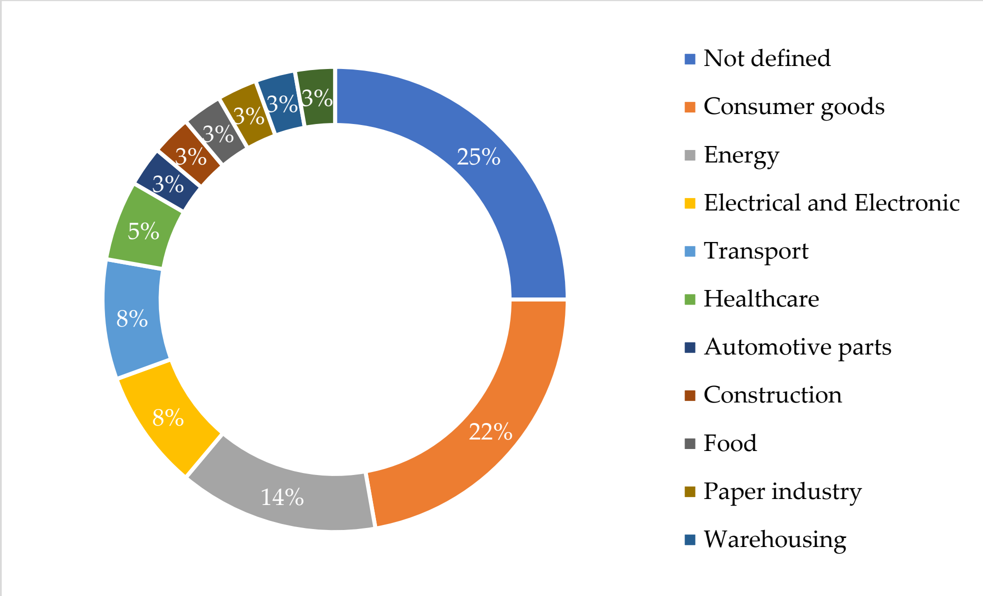

Figure 5. Distribution of publications per industrial sector of applications.

4. Discussion

Researchers show an interest in these designs thanks to their contributions to economic, social, and sustainable competitiveness, as indicated by [19]. The SC analysis can be reinforced in a closed network model that involves the integration of customized direct and reverse logistics for several problems. These structures need to include the amount and quality of return products, sources, and constraints [6,7,34]. Complexity in SC designs considers more levels with multiple products, and by including potential variability in different echelons [1,4,14,25,26,28,35].

The main purpose is to reduce or minimize carbon emissions and to reduce waste production (see Figure 4). Green SC management is being increasingly contemplated by some countries and industries to develop SIM approaches that consider increased revenue while reducing waste and minimizing energy costs [4,19,20,44]. The impact of environmental government regulations on inventory costs should be studied [20,40]. The S aspect of sustainability is poorly studied, which makes it a future research opportunity.

There is a growing need for models to integrate all relevant factors, such as inventory, production, disassembly activities, and transport for collection or distribution. Incorporating location, vehicle routing problems, and transport modes, and considering the variability of delivery times, loading and unloading times, and truck capacity may better reflect reality [17,19,26,44,47]. Extending inventory problems by contemplating location and transport issues is an opportunity to help to develop new models for SIM models in SCs; for instance, inventory costs, fixed and variable warehouse operating costs, the total cost at the destination, including production and delivery costs [5,31].

Models should deal with a more complex system that considers uncertainty by developing stochastic methods to contemplate demand and supply uncertainty, vehicle breakdowns, return products supply, or capacities [14,28,30,31,35]. For further research purposes, the development of integrated sustainable SC models should be enhanced to incorporate the whole sustainability dimension, including social aspects such as job satisfaction, worker welfare, and occupational safety [5,21]. The inclusion of multi-objective models is fundamental for practitioners and researchers, and the most widely applied approach to model such problems is mathematical programming, mainly with a single objective and solved by exact methods. So, developing multi-objective models that simultaneously incorporate the three sustainability pillars is essential [16,29,34]. A promising way to solve these problems is to develop and apply new algorithms and heuristics [26].

Finally, a roadmap (Figure 6) to identify trends and future directions in relation to each classification criterion is proposed.

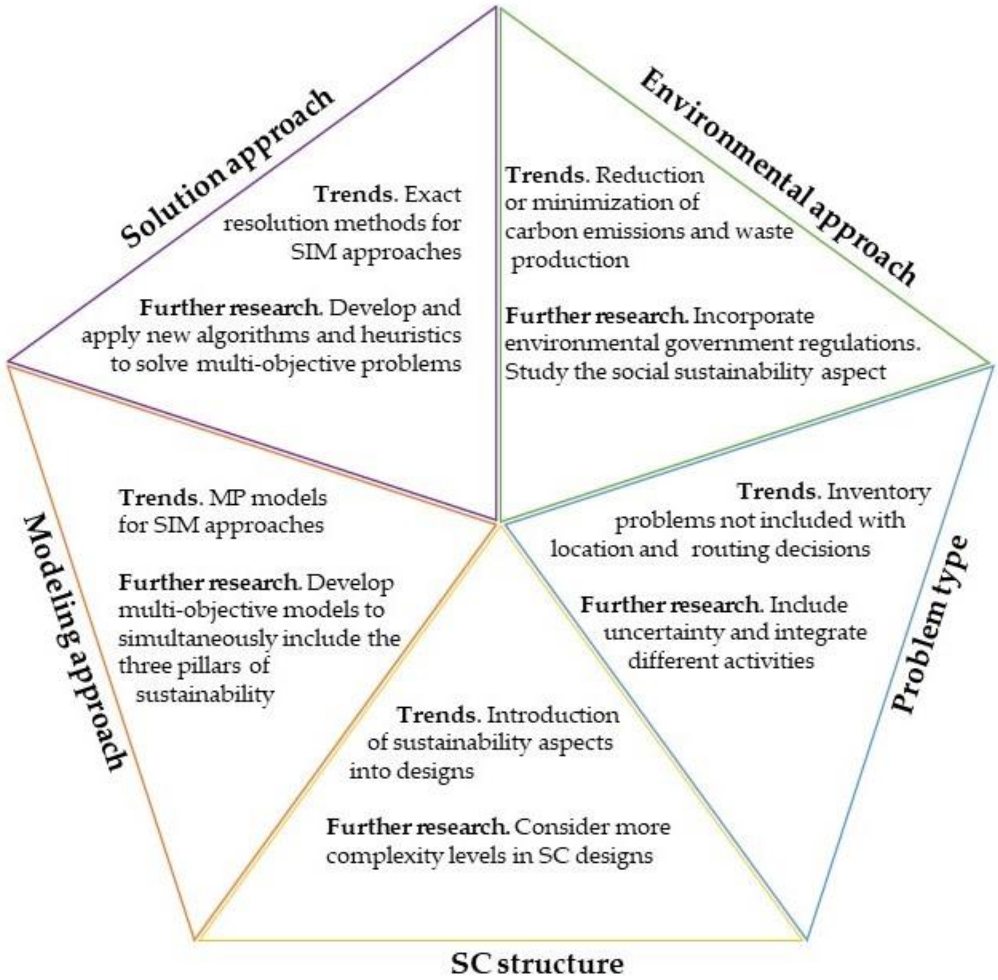

Figure 6. Roadmap of trends and further research lines.

First, regarding environmental aspects, the trend of studies focuses on reducing or minimizing GHG emissions and on minimizing waste generation in production activities. For future studies, we identify that SIM models should incorporate environmental government regulations about inventory costs and also incorporate the S sustainability issue. Second, inventory problems are considered in isolation regardless of facility location and transportation routing decisions. Therefore, we propose integrating inventory, production, disassembly activities, and location decisions into SIM models, as well as transport for the collection and distribution of returned products. It would also be desirable to consider the uncertainty about the amount and quality of returned products, sources, and constraints. Third, sustainability is introduced by designing the supply network mainly through reverse logistics and closed-loop SCs (CLSC). With this criterion, future research should consider more complexity levels in SC designs using multiproducts and the potential variability in different SC echelons. Fourth, the development of MP models, specifically single-objective models, is a trend in SIM modeling approaches. For further research, it is advisable to develop multi-objective models to simultaneously deal with the three sustainability pillars; EC, EN, and S. Finally, on MP models, the most widely used solution approaches are exact methods. For future models, we propose developing and applying new algorithms and heuristics to solve multi-objective SIM problems.

5. Conclusions

This article provides an overview of the scientific literature on SIM models in the SC context. It is specifically oriented to identify, select and analyze the main studies addressing how sustainability is being managed by SCs through quantitative inventory management models. The 36 reviewed articles are categorized according to the subsequent classification criteria: SC structure, environmental approach, problem type, modeling approach, and solution approach.

From the reviewed literature and the five classification criteria, the main findings reveal that almost one-third of the studies introduce sustainability aspects into designs by incorporating reverse and closed-loop logistics, whereas the environmental approach is widely studied in the reviewed articles. Uncertainty considerations should also be included in stochastic and fuzzy inventory management models [48]. Additionally, the new results from this study can be proposed on a roadmap that contemplates the main trends and future research guidelines, based on the main limitations and future research proposals of the reviewed articles, to be addressed by SIM quantitative models (Figure 6).

The managerial insights of this roadmap are oriented to serve as an initial conceptual framework to support practitioners and researchers in articulating strategies and practices that develop and implement SIM quantitative models in SCs by, for instance, repairing and reworking defective items in local stores to maximize profits in a global SC [49].

It is worth noting that there are some limitations to this review. The consulted scientific databases were Scopus and WoS, which are constantly updated. The provided data are those collected at the time when this research was carried out. Here we review the literature published until January 2022. Despite following a systematic search process, some valuable papers may have been overlooked for this review. Models are considered in an SC context, which leaves out single-stage sustainable inventory models.

Finally, new forthcoming works are about building a high-level conceptual SIM framework based on this study and considering SC structures, sustainable inputs, quantitative models, inventory policies, and sustainability objectives, among other dimensions and elements. This conceptual framework should be the basis for novel quantitative models, such as multi-objective mathematical implementations to optimize these SIM models in an SC context in terms of EN, EC, and S factors. These new conceptual and quantitative SIM models should be applied to several real-world applications. Indeed, the authors are working to do so in the copper mining industry.

Author Contributions: The work was shared as follows: P.B. contributed with article conceptualization, methodology, data curation, formal analysis, investigation, visualization, writing original draft; J.M. and R.S. also contributed with conceptualization, supervision, resources, visualization, writing—review and editing. All the authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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

Appendix A.

Appendix A.1. Distribution of Reviewed Publications Per Journal

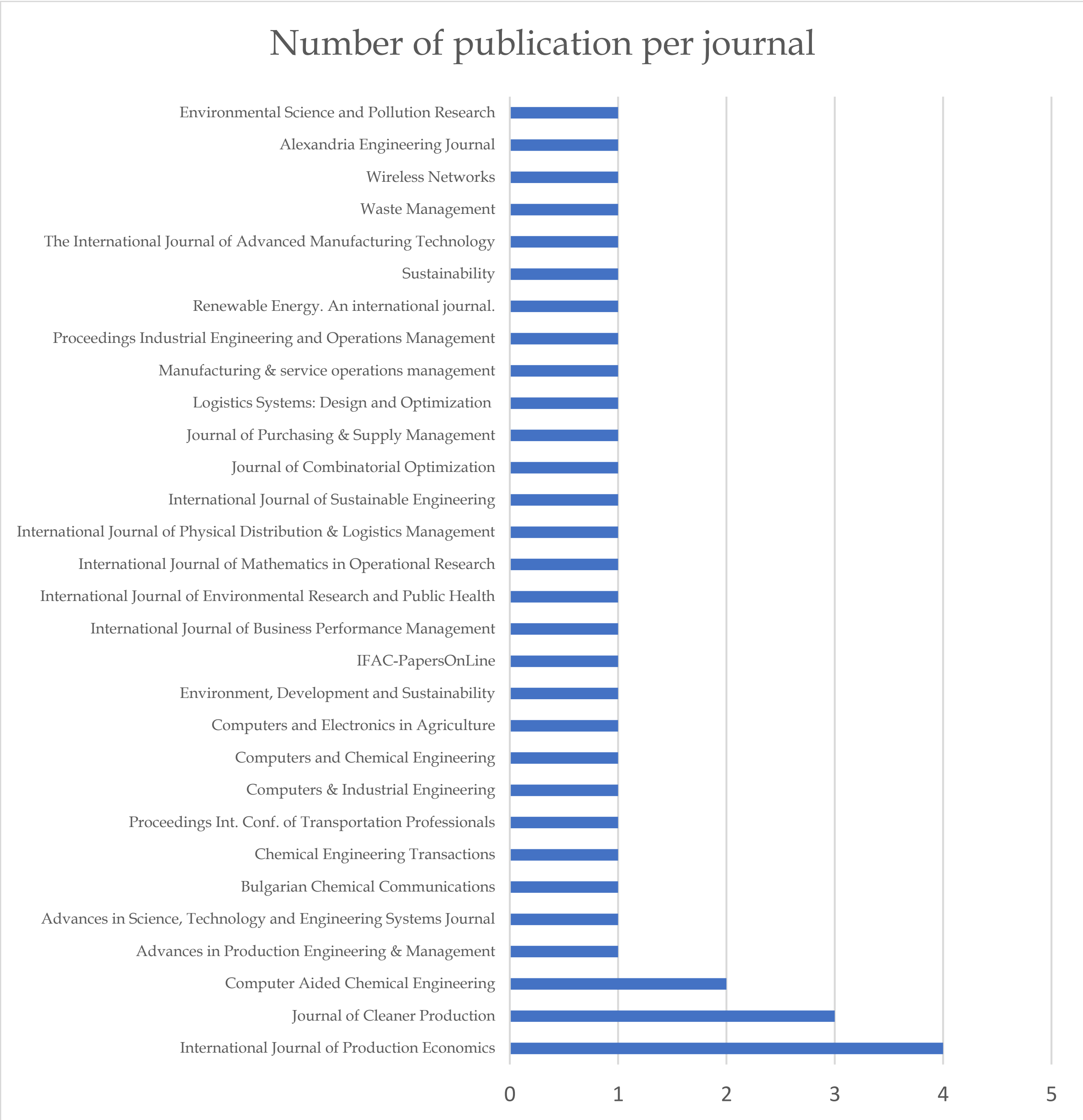

Figure A1. Distribution of reviewed publications per journal.

Appendix A.2. Sustainability Aspects, Research Methodology, Objectives and Proposed Further Research Per Article

Table A1. Sustainability aspects, research methodology, objectives and proposed further research per article.

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Pati et al. [40]	X	X		Empirical	Formulate a linear analytical model which minimises the total reverse logistics costs for multivariety recycled waste reverse logistics systems (RWRLS) subjected to constraints that take into account various internal and external factors that affect RWRLS.	Formulate a cost optimization model that considers the impact of various government regulations on the recycling industry.
Bostel et al. [31]	X	X		Conceptual	Review the applications, case studies, models and techniques proposed for the design, planning and optimization of reverse logistics systems.	There is a growing need for models to integrate all relevant factors, i.e., inventory management, production or disassembly activities, as well as transport activities, for collection or distribution planning. There is also a need for specialized models adapted to realistic specific cases. Regarding strategic models, the data of the return flows and models should, therefore, incorporate stochastic features or be robust for the uncertainty of the supply of return products.
Dekker et al. [18]	X			Empirical	Determine with a simulation experiment what strategy is the most efficient one of the proposed strategies in the inventory management area by considering the use of temporary storage offered by intermodal transhipment points to position some stock of fast-moving consumer goods in advance of demand.	Apply floating-stock requires batch production, a somewhat predictable demand (in volume terms), containerised transport and a standardised product mix.
Ross et al. [36]	X	X		Exploratory cross-sectional	Develop managerial insights related to the management and repositioning of the empty reusable container inventory.	Address the container supply risk issue at all three types of port operations. This approach would examine variations in container ability with a view to minimize variation in container overstock and shortage.
Kuo [32]	X	X		Empirical	Simulate and construct a manufacturing/remanufacturing model by means of different inventory management strategies and variables.	The lean principle, material requirement planning in remanufacturing and forecasting in remanufacturing could be used to revise this research model. The satisfaction between customer and remanufacturer could also be studied.

Table A1. *Cont.*

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Nativi and Lee [15]	X	X		Exploratory cross-sectional	Investigate how Radio Frequency Identification information-sharing can help SCs that use reverse logistics to increase environmental and economic benefits through more coordinated inventory management.	An adaptive information-sharing policy must be proposed to remain economically beneficial when drastic changes in the SC configuration occur. Study how the government's role affects players' economic performance. Government regulations can also help to motivate manufacturers, suppliers and third-party collectors to increase returns, but it is necessary to identify how incentives or penalties are assigned to achieve the best system improvement.
Zhang et al. [38]	X	X		Empirical	Develop a simulation model for SC management to include the selection of the optimal biofuel facility location, logistics design, inventory management and information exchange.	Refine the model to incorporate data uncertainty and model uncertainty, and also include inventory holding costs.
Nikolopoulou and Ierapetritou [30]	X	X	X	Conceptual	Review research on sustainable chemical processes and SC, and identify the emerging challenges and future opportunities in this area.	Develop stochastic methods capable of capturing uncertainty effects. Define an appropriate performance measure for the accurate and efficient assessment of network operations to devise new modeling systems and solution techniques for SCM. Examine integrated methodologies by combining two sustainable approaches or more (e.g., inventory management, production planning, product recovery, etc.)
Arikan et al. [1]	X	X		Empirical	Analyze a serial inventory system through the indirect effect of transport lead time variability with the replenishment policy on SCs economic and environmental performance.	Consider more SC levels and include the potential variability at different echelons. Production lead time at the supplier site and the transportation time on road/rail from the supplier to the port, and from the central warehouse to further stocking points and customers, are potential causes of variability and inefficiency in the SC. Moreover, study the consideration of different transportation modes and the combination in intermodal logistics networks.
Zhang et al. [25]	X	X		Empirical	Develop a multi-echelon multiperiod solid waste management system by inoculating with multi-echelon SCs to minimize the system cost with cost-effective allocations of waste flows and disposal rates at waste management facilities.	Integrate either interval programming to deal with uncertain data or integer programming to plan the capacity expansion problem of disposal facilities, transportation load or inventory. Design a multiwaste, multi-echelon, multi-uncertainty SC of the waste management network.

Table A1. *Cont.*

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Battini et al. [3]	X	X	X	Empirical	Propose a new easy-to-use theoretical model to calculate a sustainable EOQ, called S-EOQ, and study S-EOQ compared to the traditional approach (EOQ).	Study the trade-off between costs and emissions by analyzing the influence of changes in a set of key parameters. Apply an integrated point of view to the sustainable lot sizing problem, in which the whole SC is involved in sharing costs (and not only one firm).
Fichtinger et al. [5]	X	X		Empirical	Build an integrated simulation model to examine the interaction between inventory and warehouse management. Highlight the key effects of inventory management on warehouse-related greenhouse gas emissions.	Consider variable and fixed costs of operating warehouses in a joint inventory and warehouse cost optimization problem. Analyze the integrated warehouse and inventory management in a larger SC context by contemplating the total landed cost, including manufacturing and transport costs. Work in a sustainable warehouse management by integrating economic, social and environmental goals. Increase the efficiency of inventory management and warehousing processes to reduce their environmental impact and to contemplate worker welfare, job satisfaction and occupational safety.
Ugarte et al. [44]		X		Empirical	Quantify the difference in greenhouse gas emissions between a traditional EOQ inventory policy and each lean-oriented inventory management practice.	Study fundamental impacts, such as the water footprint of lean practices, from an international stand point.
Yılmaz Balaman and Selim [39]	X	X		Empirical	Develop a decision model for the sustainable design of biomass based on renewable energy SCs and district heating systems (DHS) with thermal energy storages. The model integrates strategic decisions, such as location and capacity selection for energy plants, DHS, thermal storages and biomass storages, with tactical decisions related to biomass production, supply and transportation planning, inventory management and energy production.	Develop a model to handle bioenergy SC design problems in various regions with different types of feedstock and transportation modes. Include the additional case-specific constraints required by the problem.
Calmon and Graves [33]	X			Empirical	Describe, model and optimize inventory in a reverse logistics system that supports warranty returns and replacements for a consumer electronic device.	Extend the modeling and analysis to relax the assumption that the price at which refurbished devices can be sold in a side channel is nonincreasing.
Tsolakis and Srai [19]	X	X	X	Empirical	Develop a system dynamics model to investigate inventory planning and control operations of crude sulfate turpentine as the source of renewable terpenoid feedstocks, and 'green' paracetamol as the commercial medication, to support the design of SC operations for the emerging bio-based chemicals market.	Promote effective operations management research about 'green' medications and outline robust policy-making interventions.

Table A1. *Cont.*

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Takeda Berger et al. [45]		X		Empirical	Simulate different inventory management strategies for finished products in a supplier-customer relationship in a lean SCM environment.	Develop a model that contemplates variability in transportation time, loading and unloading times and truck capacity. Explore the model's influence on the involved costs by quantifying the impact of lead time and service level.
Ivanov [16]	X	X	X	Empirical	Design optimal integrated bioethanol SCs for waste management in the biofuel production and usage process.	Incorporate uncertainty into demand, production and harvesting parameters.
Amer et al. [23]	X	X	X	Empirical	Develop a simulation model of a two-echelon real-life SC to study the effect of changing the order quantity with uncertain demand and lead time on a set of economic, social and environmental performance measures.	Study the effect of different transportation modes, or multimodal, on SC sustainability, as well as the effect of distinct water transportation types of either container shipment or reefer shipment on performance.
Sun et al. [26]	X	X		Empirical	Propose an optimization model to minimize the total cost formula for a location-inventory-routing problem by considering food waste and fuel consumption.	Develop an efficient heuristic algorithm to handle middle-scale and large-scale instances to use multiple products and to vary shelf lifetimes for perishable products.
Yang et al. [37]	X	X		Empirical	Investigate the new containers ordering decision and the production decision with reusable containers through a discrete-time Markov decision process (MDP).	Enrich the model with more inventory decisions and necessary restrictions. Extend the model to a semi-Markov decision process that considers the randomness of delivery/production processes.
Guo et al. [34]	X	X		Empirical	Develop a mixed-integer nonlinear programming model to optimize the facility location, facility-customer assignment and inventory replenishment decisions simultaneously, and also design a novel self-adaptive differential evolution algorithm to efficiently solve this model.	Extend to a location-inventory-routing problem by incorporating the vehicle routing problem. Consider different assignments between hybrid distribution-collection centers and customer zones in different markets.
Ching et al. [27]	X	X	X	Empirical	Apply the system dynamics framework to model perishable inventory systems and to design policies that benefit the environment and the economy by reducing waste production and increasing the viability of the goods reaching customers.	Apply system dynamics to evaluate and improve policies in a wide variety of cases.
Halat and Hafezalkotob [20]	X	X	X	Empirical	Apply a Stackelberg game between the government and a multistage green SC (GSC), in which the government's goal is to maximize social welfare and that of the GSC is to minimize its cost.	Consider complex inventory management assumptions, such as deteriorating products and delayed payment, during demand uncertainty. Engage the rewards-driven systems and maintenance scheduling concepts with GSCM.

Table A1. *Cont.*

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Tighazoui et al. [35]	X			Empirical	Determine the optimal capacities of the manufacturing and remanufacturing stocks, purchasing warehouses, transport vehicles, and the optimal percentage of end-of-life returned products.	Model a more complex system that considers a random demand, vehicle breakdowns and several cities to be satisfied.
Paam et al. [28]	X	X		Empirical	Investigate the impact of inventory management optimization through a mathematical programming model on fruit loss, and inventory and processing costs, in apple SCs by proposing new inventory policies about high-tech storage room configuration.	Extend the problem to a multiproduct food SC or other fruit and vegetable industries in other geographical locations. Investigate the effects of storage technology on apple prices and sales of top-quality fruit at a higher price than medium-quality fruit. Incorporate demand or supply uncertainty, and integrated decisions, such as harvest inventory or inventory-transportation and risk analysis.
Chen et al. [4]	X			Empirical	Determine efficiently the optimal product image location, product price, and procurement quantity that maximize the profit.	Incorporate loss of stockouts into the model based on the health care system. Focus on the estimation of price and space elasticity of various supplies.
Al-Haidous et al. [21]	X	X		Empirical	Develop a multi-objective mathematical model for shipping fleet scheduling, routing and delivery for sustainable liquified natural gas SCc. The model incorporates flexibility in delivery times; inventory management and berth availability constraints; and fuel consumption and carbon emissions.	Consider multidischarges on the same route, ship-to-ship transfer operation and alternative routings between Asia and Europe. Capture all the sustainability dimensions at higher resolutions.
Mohammadnazari and Ghannadpour [24]	X	X	X	Empirical	Present a mathematical programming formulation to solve the problem of ordering the required amount to project site, while taking into account an ancillary warehouse.	Integrate location decisions into the model formulation to find the best warehouse location.
Ganev et al. [17]	X	X	X	Empirical	Propose a mixed integer linear programming model to optimize the strategic design of a sustainable integrated biodiesel/diesel SC using first- and second-generation bioresources for biodiesel production, such as sunflower and rapeseed, waste cooking oil and animal fats, by considering all the sustainability aspects: economic, environmental, social.	Incorporate uncertainty into demand, production and harvesting parameters.

Table A1. *Cont.*

Reference	Sustainability Aspects			Research Methodology	Objective	Proposed Further Research
	EC	EN	S			
Žic and Žic [22]	X	X		Empirical	Analyze correlation and interdependencies among inventory levels, costs and greenhouse gas emissions from replenishments within SC echelons using simulation-based inventory optimization conducted in 4000 experiments by assuming the conditions of: stochastic market demand, (*R*, *s*, *S*) inventory policy, target fill rates, predefined lead times, closing days constraint.	Consider a multi-echelon inventory system with different inventory policies.
Wang et al. [29]	X			Empirical	Propose a practical integrated scheduling model for a port-centric SC considering the particularity of neighboring-port manufacturing, uncertain arrival delay and departure time caused by variable draft requirements and dynamic tidal levels with a mathematical optimization model that aims to minimize the overall cost.	Consider multimode land transportation. Different transportation modes have distinct scheduling rules, and landside transport scheduling can have a nonnegligible impact on the overall results.
Ali et al. [14]	X	X		Empirical	Design a multi-echelon reverse logistics network, and propose a mixed integer linear programming model that considers a number of facilities and product returns with different recovery options to minimize total expenses.	Incorporate uncertainty about the amount and quality of return products, sources and constraints, and some constraints, such as capacity and demand, that can be considered fuzzy, as well as objective functions. It can be strengthened in a closed network model, which is the integration of both forward and reverse logistics, and can be customized for different problems.
Ahmadini et al. [41]	X	X		Empirical	Formulate a multi-item multi-objective inventory model with back-ordered quantity incorporating green investment in order to save the environment	Incorporate continuous price and or price break in the items. Furthermore, late delivery and shortages of items can be considered as an extension of the proposed model. Further, deteriorating items with expiration duration could be possibly considered as an extension to this work.
Tavana et al. [43]	X	X		Empirical	Propose a novel bi-objective mixed-integer linear programming model to solve the location-inventory-routing problems in green supply chains with low-carbon emissions under uncertainty.	Consider supplier's score through multi-criteria decision-making approaches from economic, circularity, and social perspectives. Is suggest developing an efficient meta-heuristic algorithm to solve large-size instances of this problem.
Rout et al. [42]	X	X		Empirical	Design a bi-objective model minimizing both total cost and overall emissions simultaneously subject to a well-built set of constraints. The model focuses on obtaining a trade-off between cost and emissions, thereby determining the optimal production–shipment policy and a proper routing plan for the fleet of vehicles.	Extend the model in an uncertain environment, be it random or fuzzy.
This paper	X	X	X	Conceptual	Literature review of SIM quantitative models in an SC context	Propose new conceptual frameworks and optimization models for SIM in an SC context

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