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Review

The New Generation of Operations Research Methods in Supply Chain Optimization: A Review

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Abstract: The possibilities of applying Operations Research (O.R.) techniques in the design of real-world systems are vast. The optimization and design of the supply chain network (SCN) is one of the relevant topics that has directed the attention of many scholars. Sound decisions in this regard, including the proper selection of the facility's location, transportation modes and routes and inventory management policies, can noticeably improve the systems performance. Over 380 articles published between 2005 and 2016 in the ISI/Web of Science database have applied advanced O.R. techniques in SCN optimization studies. This paper offers a systematic review of these published contributions by focusing on two categories of O.R. approaches most recently applied for the design of SC systems: integrated mathematical modeling and simulation-optimization (S-O) frameworks. A taxonomy analysis of the mentioned approaches is presented based on the supply chain elements. A bibliometric analysis is also conducted to provide technical insights into the possible gaps in the field. Moreover, the relevant studies on SC sustainability are highlighted. The research results are supportive of the S-O frameworks as either an alternative approach or an effective solution method for the integrated problems. The research outcomes can provide researchers in the field with useful details of the integrated problems and S-O frameworks as the most recent O.R. methodologies in the field of SC optimization.

Keywords: optimization; simulation; integrated problems; S-O framework; supply chain; sustainability; network design

1. Introduction

In a globalized and highly competitive business environment, supply chain management (SCM) has become more prominent than ever before, because the competitiveness of a company is strongly dependent on the performance of its supply chain (SC). In a broad sense, SC comprises all of the activities from purchasing of raw materials, to the manufacturing and distribution of the final products and reverse logistics. Owing to the fact that the SC activities of a product cannot be designed in a stand-alone and isolated way, this wide range of operational activities should be working together and follow asystem-wide strategy that is determined in a global optimization approach [1]. In the past few decades, different policies have been taken into consideration for the optimization of the SC activities. The emergence of lean SC was the first significant milestone, where cost reduction, flexibility and process improvement were targeted through the minimization of different types of wastes in the system [2]. After a few years, agility was introduced as a competency with the aim of developing an SC with a high ability to respond to the market changes [3]. Meanwhile, climate change and global warming gradually became the major concerns of international society. Since then, the green concept has evolved rapidly to reduce pollution and the negative environmental impacts of SC activities [4]. On the other hand, the disruptions in the normal flow of SCs that have been caused by recent natural and man-made disasters directed attention toward risk-related research topics, i.e., statistical modeling of SC risks [5] and SC resilience [6]. Although each of the mentioned agendas emerged to respond to a distinct problem and some of them are conflicting in nature, harmony between the mentioned concepts can benefit the broad concept of sustainability. From cost effectiveness as the most entrenched measure, to different types of responsiveness [7], and so-called sustainability as the most recent and comprehensive concept that is still in its infancy stage, all need methodical approaches to be applied to improve the SC activities.

Supply chain network design (SCND) as a fundamental topic in this regard has taken place among the Operations Research (O.R.) studies since the formation of SCM in 1980s. The O.R. tools, more particularly optimization and simulation approaches, have been applied widely in the literature to improve SC performance. Optimization has provided managers with a powerful platform in the decision making process. Moreover, the simplified representation of the SC generated by simulation can capture details and the dynamic behavior of the system. Simulation modeling can also assist users to perform what-if analysis in the most effective way. However, both techniques have their own pros and cons.

According to Farahani et al. [8], the design of the supply chain network (SCN) is a strategic decision, which has long-term effects and can be affected by a variety of decisions at the tactical (like inventory and transportation policies) and operational (like pricing and service quality) levels. Due to the interdependency among different elements of an SCN, the overall optimality of the network might be unwarranted by individual optimization of the variables in each element. However, inclusion of too many decision variables increases programming difficulties, which in turn reduces the effectiveness of the mathematical model. On the other hand, simulation can provide a more detailed overview of the overall system in a user-friendly manner, although it is not a proper tool for the optimization of real-world and large-scale systems. These deficiencies necessitate the development of new approaches to overcome them.

Studies on conventional mathematical models for the individual optimization of each of the SC elements were formed decades ago. However, the literature on integrated mathematical models and simulation-optimization (S-O) approaches has only become popular during the past few years, because the conventional methods are no longer effective in the design of complex systems. Moreover, a more practical solution addressing the real-world uncertainties than that generated by a stand-alone optimization model can be achieved through the application of simulations [9]. The literature on O.R. techniques in SCND is well supplied by review papers on integrated mathematical models. Of the only two review papers in the field of S-O frameworks, the one by H-Barrientos et al. [10] merely analyzed the scientific collaboration patterns, and Jalali et al. [11] focused on S-O methods in inventory studies by categorizing the published papers based on echelons, items, horizon, lead time and inventory policy. To the best of our knowledge, however, no broad overview of the S-O methods has discussed the recent evolution in the SCND. Moreover, the position of the S-O frameworks needs to be clarified relative to the integrated mathematical problems. To this end, this paper reviews the published contributions in the mentioned fields accompanied with a bibliometric analysis, in order to give insights into promising research directions for the future studies. In addition and owing to the fact that sustainability has become the first and foremost focus in the modern SC [12], studies in this regard are highlighted to contribute to this trend. The remainder of this article is organized as follows. After an overview of the present study, the major conventional mathematical models are given in brief; integrated mathematical models are detailed; and the published S-O frameworks in SCND are reviewed. A discussion on the studies on sustainability in the mentioned fields comes next. Finally, the S-O frameworks and integrated problems in SCN design and optimization are compared and contrasted, and the study conclusions and suggestions for the future research directions are presented.

2. Overview

A brief review of the literature on O.R. approaches in the SC context from 2005–2016 demonstrates an exponential increase in the number of published papers and in the variety of the methods and models for SCN optimization and design. The present paper applies a systematic review in two steps:

one for integrated problems and the other for S-O frameworks in the context of SC, from the perspective of SC elements. The former step is straight forward, where the following keywords are used: "location routing", "location inventory" and "inventory routing". However, the latter step requires more attention. First of all and in the perception of SC elements—facilities, transportation, inventory, information flow, sourcing and pricing (according to Chopra [13])—different pair-wise combinations using the mentioned keywords were searched. In parallel, the main context was combined with an S-O framework, by searching the keywords "simulation optimization" in the title field.

The first-step search resulted in 38 articles in location-inventory, over 122 in inventory-routing and 129 in location-routing models, including the journal papers from the major ISI database: Web of Science. In the next stage, over 300 articles on the S-O frameworks were collected, and a database file of titles, author's names, years, journal names, keywords and abstracts was developed. From reading the abstracts in the S-O frameworks, the papers not relevant to the study scope were excluded, and 44 articles remained for further consideration. In the next step, the methodology and conclusion parts of the articles were reviewed to add the relevant information, such as the contribution, the application area and the features of the proposed models, to the database. The features considered were stochastic vs. deterministic, linear vs. nonlinear and single objective vs. multiple objective (M-O). The first two features were chosen to examine the complexity of the problem and the latter one to particularly highlight sustainability in the developed models.

Figure 1 shows the 11-year trend in the number of published papers in each of two groups of reviewed O.R. approaches, where more than 85 percent of articles are published by the top contributing journals listed in Table 1. As shown in Figure 1, S-O frameworks in the context of SC optimization are transitioning from an emerging subject to a growing research area since 2010. Conversely, the location-routing topic has become saturated during the past few years, and a decline in the trend of inventory-routing problems after 2014 can be seen. According to Table 1, the top journal in both the integrated problems and S-O frameworks in terms of the number of published papers is the European Journal of Operational Research by 46 and 15 articles, respectively. The key contributing scholars in terms of the number of contributions in integrated problems is Gilbert Laporte with 13 papers, followed by Caroline Prodhon and J.F. Cordeau with 11 and 10 papers, respectively. Among the S-O studies in general, B. Datta is the key contributing author in the context of SC, while most of the other scholars contributed once to the subject matter. The top cited article among the integrated problems belongs to the location-routing problem (LRP) category [14], proving the popularity of this family of models over the other integrated problems. Among the S-O studies, the research paper by J.Y. Jung [15], titled "A simulation based optimization approach to supply chain management under demand uncertainty" has received the most citations thus far. In the following sections, a more detailed bibliometric analysis is conducted, and the research trend and promising research gaps are discussed.

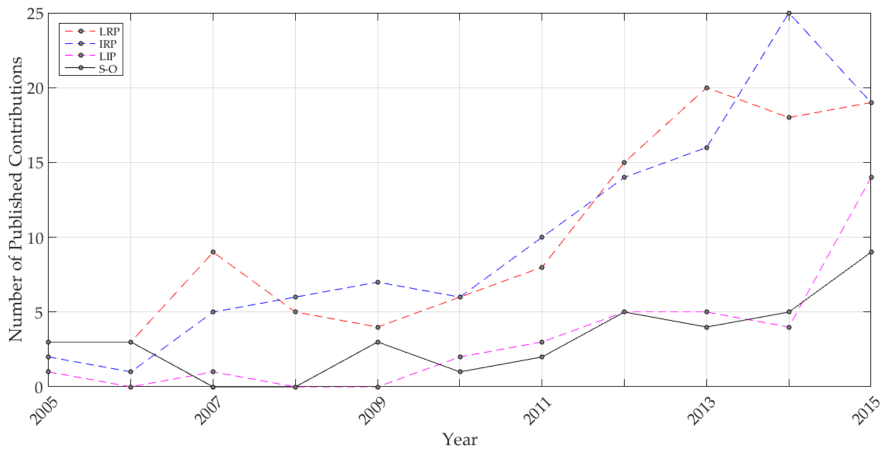

Figure 1. Publication frequency by type/year: 2005–2015. LRP, location-routing problem; IRP, inventory-routing problem; LIP, location-inventory problem.

Table 1. The top contributing journals based on the number of published papers.

Journal	# of Papers		Journal	# of Papers	
	I.P. [1]	S-O		I.P.	S-O
European Journal of Operational Research	46	15	Water Resources Management	0	14
Computers Operations Research	37	3	Operations Research	10	3
Computers Industrial Engineering	18	10	Informs Journal On Computing	5	7
Transportation Science	26	0	Simulation Transactions Of The Society For Modeling And Simulation International	0	12
Int. J. Of Production Economics	17	6	Int. J. Of Advanced Manufacturing Technology	6	5
Expert Systems With Applications	11	5	Computers Chemical Engineering	3	7
Int. J. Of Production Research	10	6	J. Of The Operations Research Society	5	4
Simulation Modelling Practice And Theory	1	14	Annals Of Operations Research	4	5
IIE (Institute of Industrial Engineers) Transactions	1	13	J. Of Water Resources Planning And Management	0	8
Transportation Research Part E	14	0	Naval Research Logistics	5	3

[1] Integrated problems.

3. Conventional vs. Integrated

The diversity of SC-related analytical studies in the literature includes facility location problems, routing problems, inventory management problems, supplier selection and pricing models. The mentioned studies have mostly developed mathematical models to solve SC problems. The specialized nature of the logistical elements of SC—facility, transportation and inventory—in SCND made us focus on this area. However, the cross-functional elements of sourcing, pricing and information are discussed in cases where these elements are incorporated into the integrated problems. In this study, consideration of the decision variables of a single SC element is termed as conventional modeling, while concurrent consideration of decision variables from different SC elements/decision making levels is termed integrated modeling.

In the simulation literature, logistical elements have received much more attention than the cross-functional elements. Among the logistical elements, facility location planning has been studied more than routing and inventory problems. In the optimization literature, however, routing problems have been at the center of attention. Nevertheless, due to the interdependency among the decision variables from each of the mentioned conventional models, the optimality of the network cannot be guaranteed by addressing the SC element as an individual. To this end, integrated mathematical models have emerged to optimize the SC variables and design the SCN. Melo et al. [16] systematically reviewed the facility location problems and examined the feasibility of integrating facility location decisions by variables from the other SC elements. Despite the numerous inventory-related articles in proposing mathematical and simulation models to solve real-world problems, no comprehensive review has been conducted on this research topic. This might be due to the fact that inventory models have recently been used as a complementary part of integrated mathematical models, while the conventional/stand-alone approaches are no longer popular (i.e., the famous Economic Order Quantity model—EOQ extensions that are the basis of many studies).

The literature of routing problems has recently been reviewed by Diaz-Parra et al. [17]. They attempted to classify different types of transportation problems by reviewing the proposed mathematical models and algorithms. They categorized the related problems into the following major groups; bus scheduling problem, delivery problem, combining truck trip problem, vehicle routing problem, helicopter routing problem, truck loading problem, truck dispatching problem, truck routing problem, truck transportation problem, travelling salesman problem and variants, convoy routing problem, railroad blocking problem, air traffic flow management problem and inventory routing problem. Except the last category, which can be grouped as an integrated approach, they are all pure transportation problems with a focus on routing decisions.

The main objective of the integrated problems is the minimization of the total cost, while the other aspects, such as service quality, carbon emission and risk, are considered in the literature as the secondary objective. Z.J. Shen [18] briefly reviewed the integrated SC optimization models prior to 2007, where the main focus is on the design of a three-tiered SC system. The author also presented some general models considering the impact of routing cost, reliability and flexibility on decision making in SC. However, few integrated models were available at that time, and the review was as short as a few pages. Moreover, the author did not mention the important aspects such, as multi-objective programming and the solution algorithms, as it was not the major trend at that time. In effect, the next section is organized to update this field.

4. Integrated Problems

SCND is the most important strategic issue in SCM. Although the facility location, routing and inventory decisions belong to different levels of decision making in an SC, they are interdependent, and the overall optimality might be unwarranted in the case of individual design and optimization. The integrated models have been devised to settle this issue. The location-inventory problem (LIP), the location-routing problem (LRP) and the inventory-routing problem (IRP) are the major classes of integrated problems in the context of SC. LRP models are the subject of most published papers of this type, where about 40 percent of the studies merely aimed at proposing solution algorithms to solve LRP extensions. The integrated models are basically developed for optimizing the variables from more than one of the logistical elements of SC. Several of these studies, however, incorporated sourcing (supplier selection) and pricing (revenue management) decisions into the model. According to Figure 2, an increasing number of integrated problems has been cited by the other disciplines in the past few years, which demonstrates the tendency of researchers to utilize this recent generation of O.R. approaches. However, it is worthwhile to note that the citation of LRP papers is growing steadily, while that of IRP papers has faced a decline since 2014. The top-five individual papers in each of the integrated problems are also listed in Table 2 to introduce the key cited contributions with respect to the citation reports. Since the total number of received citations by a paper cannot reflect the effectiveness of that study, comparing the old published papers with the recent ones is not appropriate. To this end, the average citation measure is calculated so that they can be compared in a rational way and using a relative measure.

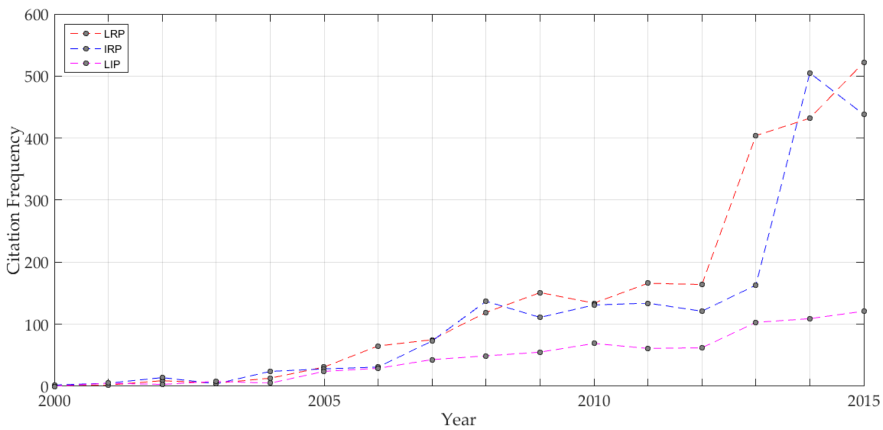

Figure 2. Citation frequency by year: 2000–2015.

As a final overview to the research area of integrated problems, Tables 3 and 4 show useful information on the top research areas and the top contributing organizations in the field, respectively. These two tables together can assist young researchers and students to recognize the top target universities to pursue their study/research career, considering their field of interest. As was expected, O.R. is the key research area to the integrated problems, followed by industrial engineering and management. In a cumulative basis, Canadian universities are the leading contributing organizations in the field, followed by Iranian and American universities/research institutes.

Table 2. The top cited articles in each category of integrated problems.

LRP			IRP			LIP		
Item	TC [1]	AC [2]	Item	TC	AC	Item	TC	AC
Nagy and Salhi (2007) [14]	254	25.4	A.J. Kleywegt et al. (2002) [19]	135	9.0	Z.J.M. Shen et al. (2003) [20]	252	18
H. Min et al. (1998) [21]	206	10.8	A.M. Campbell et al. (2004) [22]	96	7.4	J.-R. Lin et al. (2013) [23]	22	5.5
T.H. Wu et al. (2002) [24]	139	9.3	A.J. Kleywegt et al. (2004) [25]	73	5.6	J.-S. Tancrez et al. (2012) [26]	22	4.4
Tuzun and Burke (1999) [27]	128	7.1	D. Adelman (2004) [28]	73	5.6	A. Atamtuerk et al. (2012) [29]	21	4.2
Barreto, Sergio et al. (2007) [30]	86	8.6	L. Bertazzi et al. (2002) [31]	77	5.1	Z. Wang et al. (2007) [32]	26	2.6

[1] Total citation; [2] average citations per year.

Table 3. The top 5 research areas in each category of integrated problems.

LRP		IRP		LIP	
Research Area	No.	Research Area	No.	Research Area	No.
Operations Research MS [1]	90	Operations Research MS	84	Operations Research MS	35
Engineering	56	Management	30	Engineering Industrial	19
Computer Science	43	Engineering Industrial	29	Management	10
Business Economics	32	Computer Science IA [2]	27	Engineering Manufacturing	9
Transportation	21	Transportation Science Technology	21	Computer Science IA	9

[1] Management Science; [2] Interdisciplinary Applications.

Table 4. The top 10 contributing organizations in the literature of integrated problems.

Author	Country	Publication	Author	Country	Publication
University of Montreal	Canada	25	Georgia Institute of Technology	USA	14
HEC Montreal (Ecole des hautes etudes commerciales de Montreal)	Canada	21	Amirkabir University of Technology	Iran	12
University of Technology of Troyes	France	16	Ghent University	Belgium	10
University System of Georgia	USA	14	University of Tehran	Iran	9
Norwegian University of Science Technology	Norway	14	Islamic Azad University	Iran	9

4.1. Location Routing Problems

LRP analyzes the strategical, tactical and operational levels of SCM, by simultaneous optimization of routing and facility location variables. A total of 129 LRP papers have been indexed in the ISI/Web of Science database. The idea of the joint optimization of location and routing variables was first examined by Min et al. [21]. Since then, a tremendous number of researchers attempted to contribute to this topic. Table 5 lists the most contributing authors to the field, followed by Table 6 to show the key contributing nations. It is worthwhile to mention the significant portion of contributions from developing countries, like Iran, China and Turkey.

Table 5. The top 10 contributing authors in the literature of LRP.

Author	# Publication	Author	# Publication
C. Prodhon	11	A. Nadizadeh	4
C. Prins	8	C. Ferreira	4
R. Tavakkoli-Moghaddam	5	J.W. Escobar	4
V.F. Yu	4	C. Contardo	4
B.S. Santos	4	R.W. Calvo	4

Table 6. The top 10 contributing countries in the literature of LRP.

Author	# Publication	% Contribution	Author	# Publication	% Contribution
Iran	29	22.5	USA	9	7.0
France	25	19.4	Colombia	7	5.4
Canada	14	10.9	Germany	7	5.4
China	11	8.5	Spain	7	5.4
Turkey	9	7.0	Taiwan	7	5.4

The LRP models have been well acknowledged in several review papers. Nagy and Salhi [14] and Prodhon et al. [33] conducted the first and most recent comprehensive review on LRP and the extensions, respectively. In another review paper, Drexl et al. [34] systematically classified the proposed LRPs according to the following set of features: deterministic vs. stochastic vs. fuzzy data, discrete vs. continuous vs. network locations, single vs. multiple echelons, static vs. dynamic vs. periodic problems, single vs. M-O. Some of the other characteristics, such as the inclusion of inventory decisions, pickup-and-delivery LRPs, generalized LRPs, prize-collecting LRPs, split delivery LRPs and location arc-routing problems, were also discussed in this review paper. To avoid repetition, a brief discussion on LRP papers is presented here just to transfer the essentials of the topic and review the studies on sustainability in the field. The review shows that 73 percent of the published contributions in the LRP literature focused on proposing solution algorithms, where capacitated LRP is by far the most popular target model to be solved. About half of the mentioned papers put forward a new mathematical extension in addition to the solution algorithm. The majority of the LRP models belong to mixed-integer linear programming class, with only three nonlinear models of this type being found in the literature [35–37]. The other major categorization is the stochasticity of the proposed models. Twenty one of the LRP models are developed under uncertain environments among which, demand, travel time and availability of nodes are considered as the sources of uncertainty. The application of statistical distribution functions, such as Bernoulli and normal, have been used the most, while fuzzy approaches rather less often [38–41].

Nowadays, the consideration of M-O in optimization models is a common approach in academia, and LRP models are no exception to this trend. Moreover, sustainable design demands not only cost minimization, but also the optimization of measures, such as service level, social issues and risk, as well as also green factors. Twenty of the M-O contributions aimed at optimizing the above-mentioned factors. The optimization of service level measures as a secondary objective contributes most to the literature of multi-objective LRP. The proposed model by Lin and Kwok [42] is the first M-O case of this type. The same track was followed by R. Tavakkoli-Moghaddam et al. [43], where the authors aimed at service-level enhancement by maximization of the total served demand in addition to cost minimization. G. Nasab et al. [44] considered three objectives, one of which is the minimization of the population who cannot access health services due to excessive distance. Among the other relevant studies, the proposed model by Nekooghadirli et al. [45] sought to minimize the delivery time, while the maximum demand coverage was the secondary objective in the LRP model proposed by Li and Keshin [46]. The most recent integrated model of this type in the area of service level optimization is published by Liu et al. [47]. Among the humanitarian studies, three of the published contributions on LRP worked on disaster relief cases in a multi-objective basis [48–51]. All of the mentioned papers aimed at the design of distribution networks for relief goods and services in times of disaster. Rodrigues et al. [52] worked on the same humanitarian area by considering evacuation time and risk as a measure for optimization purpose.

The green issue is probably the most relevant factor to be considered for sustainable SCND. However, it has not been sufficiently addressed in the LRP literature. The first green multi-objective LRP was studied by Mohammadi et al. [53]. They developed a new model for stochastic green hub LRP with simultaneous pick-up and deliveries, to minimize emissions and the variable costs. The model developed by Govindan et al. [54] is another example of LRP that includes green objectives. Tang et al. [55] recently worked on the sustainable design of SC by considering customer environmental behavior. The integrated model in this study is also in the class of M-O problems, where the secondary objective aims at minimizing emissions. This last case incorporated inventory decisions into the location-routing model. A study by Zhalechian et al. [56] is another example where an inventory decision is also incorporated in the LRP model. In this study, the authors aimed at sustainable design of a closed-loop SCN by considering economic, environmental and social measures within an M-O LRP model.

The risk-related LRP papers have mostly tended to focus on hazardous waste network design. The research paper by Caballero et al. [57] is the first of this type, where there is social rejection of such industry by towns on the truck routes by optimizing the maximum risk as an equity criterion. This research was followed by the study by Alumur and Kara [58] who aimed to determine the location of treatment and disposal centers and the best routing schedule for different types of hazardous waste, in order to minimize transportation risks. Boyer et al. [59] worked on the same case by minimizing the risk of population exposure within a bandwidth along the particular routes. The mentioned studies only considered transportation risk, while the papers by Samanlioglu [60] and Ghezavati et al. [61] also considered the site risk. The bi-objective LRP model for the supply network of oil is another contribution in this area, where the authors focused on managerial implications and proposed an environmental risk measure using goal programming [62]. Finally, the most recent article of this type was published by Yu and Solvang [63], where the epsilon-constraint method is applied to form the Pareto optimal curve of the set of optimal solutions.

4.2. Inventory Routing Problems

The objective of a joint IRP is to assign the demand nodes to the supply ones, finding the optimal routes and then determining the inventory control decision of the supply nodes. IRP has been widely used in maritime shipping and vendor-managed inventory systems. Including the published papers on solution algorithms, more than 122 contributions have been indexed in the ISI/Web of Science directory in inventory-routing studies, in our review period of 2005–2016. Tables 7 and 8 demonstrate the basic results of bibliometric analysis in this research area, where Gilbert Laporte is the most contributing author, and in overall ranking, scholars from the USA are leading the research area in terms of the number of published papers.

Table 7. The top 10 contributing authors in the literature of IRP.

Author	# Publication	Author	# Publication
G. Laporte	11	J.H. Song	7
M. Christiansen	9	L. Bertazzi	6
L.C. Coelho	8	B. Raa	6
E.H. Aghezzaf	7	M. Savelsbergh	6
J.F. Cordeau	7	M.G. Speranza	5

Table 8. The top 10 contributing countries in the literature of IRP.

Author	# Publication	% Contribution	Author	# Publication	% Contribution
USA	31	25.4	Norway	13	10.7
Canada	20	16.3	Italy	11	9.0
France	15	12.3	Australia	7	5.7
China	15	12.3	Turkey	6	4.9
Belgium	13	10.7	Taiwan	5	4.1

Although inclusion of inventory variables in routing problems produces more precise measures for the optimality of SCN, they complicate the coding procedure. Moreover, the implementation of inventory-routing algorithms in real-world/large cases is time consuming, as evidenced by the publication of more than 80 papers on heuristic solution algorithms to solve IRPs (mostly multi-product models). There are also studies that consider the integration of decision variables from the other SCM elements. The location decision variable is included in the classical inventory routing model by Li et al. [64] and Liu et al. [65]. Another example is the integration of pricing variables by Liu and Chen [66] and production-related decisions by Bard et al. [67,68] and Magnus et al. [69].

Several of the review papers published in this area can be mentioned as reliable references for the IRP literature. "Thirty years of inventory-routing" by Coelho et al. [70] is one of the mentioned papers that classified the proposed models based on criteria, such as time horizon, fleet composition and inventory policy.

A smaller portion (less than five percent) of models in IRP belongs to the multi-objective class, compared to LRP models. Nearly all of the analytical problems and algorithms in this area aimed at total cost minimization. However, service level is the most studied secondary objective [71–76]. Two of these studies aimed at enhancing the demand coverage by the maximization of the collected rewards from the visited demand nodes [73,75]. The minimum missed order is achieved in the proposed model by Singh et al. [72], while another relevant study by Agra et al. [77] focused on the optimization of backlogged demands to improve the service level. In another example of responsive service design, Chow and Nurumbetova [76] aimed at minimizing delays in a multi-objective basis.

Among the few articles on sustainability, Soyosal et al. [78] developed a single objective model within a general framework to minimize emissions by considering it as a key performance indicator (KPI). The green model developed by Treitl et al. [79] is the first bi-objective IRP, where minimization of emissions has been deliberated as the secondary objective. Another multi-objective IRP model is developed by Niakan et al. [80] to simultaneously optimize service level and green factors. Surprisingly, only one IRP article has considered risk and social factors: Nolz et al. [81] aimed at developing a sustainable logistics system in the case of medical waste collection, considering the public health risks, the satisfaction of pharmacists and the local authority.

From another point of view, most of the published IRP papers (about 85 percent) worked on deterministic models. Nearly all of the stochastic models employed general continuous/discrete distributions to address uncertainty. However, several papers dealt with uncertainty in other ways, such as fuzzy logic [80] and chance-constrained programming approaches [78,82,83]. Less than 10 percent of IRP models are nonlinear in the objective function and/or constraint. Due to the nature of nonlinear IRP models, nearly all of the papers of this type came up with a new solution algorithm in addition to the newly-developed model [66,73,82,84–87].

4.3. Location Inventory Problems

Integrated LIP comprises the optimization of the fundamental decision variables of inventory control and facility location in the design of SCN. LIP has directed the attention of scholars only in the past few years. Including the published papers on solution approaches, 38 papers have been indexed in the ISI/Web of Science directory in this subject area. The article "A joint location-inventory model" by Shen et al. [20] was the starting point to the literature of LIP. Since 2003, the scholars in this field have contributed equally to the LIP literature (Table 9). The popularity of LIP models has been less than LRP and IRP papers. However, it is shown in Table 10 that scholars from the USA, Iran and China are among the top contributing nations in the field. The literature review by Farahani et al. [88] is a good reference to this topic. In their review, the LIP models are surveyed with the aim of providing a classification based on the solution approaches and the real-world applications of the proposed problems. In the following paragraph, a brief overview is provided to give insights to the field, while avoiding repetition.

Table 9. The top 10 contributing authors in the literature of LIP.

Author	# Publication	Author	# Publication
A. Diabat	3	H. Qu	2
Y.H. Li	3	R. Tavakkoli-Moghaddam	2
L. Wang	3	A. Unnikrishnan	2
S.H. Liao	2	G.J. Van Houtum	2
B.L. Liu	2	A.C.C. Van Wijk	2

Table 10. The top 10 contributing countries in the literature of LIP.

Author	# Publication	% Contribution	Author	# Publication	% Contribution
USA	14	28.6	Canada	3	6.1
Iran	11	22.4	The Netherlands	3	6.1
China	8	16.3	UAE	3	6.1
England	4	8.1	Scotland	2	4.1
Taiwan	4	8.1	Turkey	2	4.1

There is promising room for contributing to the literature of M-O LIP models, as only a few studies of this type can be found. Surprisingly, all of the existing M-O cases are by some means related to the optimization of customer service level [89–92]. This type also includes further relevant measures, such as the cost of lost sales by Aryanezhad et al. [93] and delay by Javid et al. [94,95]. Although social, risk and environmental factors are of much importance in the sustainable design of SCN, contributions of this type are quite rare among the existing LIP models. Sustainability in SC has been considered in two LIP articles, though neither of them is in an M-O basis. Diabat and Al-Salem [96] took the environmental aspects of the sustainable design of SCN into consideration by minimizing the cost of emissions based on the carbon credit market established by the authorities. In another relevant study, Abdallah et al. [97] presented a framework alongside the developed LIP model to allocate carbon credits to the manufacturers to address economic feasibility in the case of applying recovery to each unit of the produced part.

This review of the LIP literature finds that about 78 percent of the proposed models (30 models) are nonlinear. Nonlinearity among the LIPs is more common than in the previously-discussed integrated problems. Moreover, LIPs mostly belong to the class of NP-hard problems. In effect, about 74 percent of the LIP papers contributed to the literature by developing solution algorithms. In terms of stochasticity, Sadjadi et al. [98] employ queuing theory to deal with uncertainty. Fuzzy approaches are also applied by several LIP papers for the same purpose [50,89,99]. Some other articles [23,29,65,91,93,94,100,101] used the advantage of the probability distributions to address stochasticity, and the remaining models are deterministic.

A number of integrated LIP papers incorporated decision variables from more than two SC elements into the basic model. Kaya and Urek [102] and Ahmadi-Javid et al. [103,104] are among the very few studies of this type, where pricing variables have been jointly considered within an LIP model. Finally, there is an LIP model that includes the routing decision variables in addition to location and inventory ones [23].

5. Simulation-Optimization

Among the wide variety of S-O frameworks that have been developed under the large S-O family, simulation-based optimization, simulation optimization (optimization of simulation) and optimization-based simulation frameworks are more distinct based on the technical features. In other words, all of the published works in this area can be placed in one of the mentioned major groups based on the logic behind hybridization. S-O frameworks are flexible and applicable in various world systems. However, the present research reviews the published papers that are relevant to the SC studies. Forty four articles from the ISI/Web of Science database and the international conferences (in our review period of 2005–2016) are found. As shown in Table 11, more than half of the published contributions aimed at simultaneous optimization of variables from different SC elements, while the inventory-related studies are the second most frequently published papers in this area. This proves that the major motivation for applying the S-O frameworks has been the reduction of the problem's complexities, which are caused due to the addition of an excessive number of variables and nonlinearity, among others. As would have been thought, there is no IT-related study in this area, but the lack of attention toward the optimization of the pricing and sourcing variables is startling.

Table 11. Number of S-O papers by supply chain (SC) elements.

Rank	SC Element	Research Scope	# of Papers
1	Mixture	Optimization of variables from more than one SC element	26
2	Inventory	Inventory management variables (i.e., order quantities, reorder point)	12
3	Transportation	Routing decisions and decisions on mode and capacity of vehicles	3
4	Sourcing	Decisions on selection of the suppliers and their share	1
5	Pricing	Decisions on price changes and position (i.e., bidding strategy)	1
6	Facility	Decisions on location, capacity and functionality of each facility	1

The main categorization in this section is based on the idea behind using simulation and optimization in the simulation and optimization-based frameworks, respectively. Regardless of the purpose of hybridization, an S-O framework aims at improving the effectiveness of the analytical part. According to Figueira et al. [105], S-O methods can also be categorized considering the search method, search scheme and hierarchical order. The first two features are basically related to the solution algorithm, which mostly belongs to the technical research in computer science. However, the latter criterion describes the sequence in which the analytical model and simulation models cooperate. Table 12 demonstrates the number of S-O frameworks of each type in the context of SC. Except the frameworks developed by Nikolopoulou et al. [106], Chen et al. [107] and Almeder et al. [108], where a combination of the mentioned S-O frameworks has been employed, each distinct group of S-O studies is discussed separately in the upcoming subsections. In order to assist the researchers and students in the field to trace this emerging topic, the top research areas in the field of S-O frameworks (not limited to the context of SC), as well as information on the top contributing research organizations are summarized in Tables 13 and 14. As shown in the following tables, the O.R. field contributes most to this research area, where the sub-disciplines of manufacturing and SCM, financial engineering, revenue management, service sciences and policy modeling are the major players. Among the top contributing organizations in the field, the Indian Institute of Technology contributes most, which shows the major focus of O.R. studies in this university.

Table 12. Number of S-O papers by framework type.

Rank	Framework	Research Objective	# of Papers
1	Simulation-based	Analytic model enhancement, function evaluation, solution generation, surrogate modeling	24
2	Optimization-based	Optimization of controllable parameters in the simulation modeling of the SC system (i.e., agent-based systems)	9
3	Simulation Optimization	Optimization of the search procedure in order to minimize the total number of simulation runs and the execution time	7
4	Hybrid	Combinations of the three major categories	4

Table 13. The top 10 research areas in the field of S-O.

S-O Frameworks			
Research Area	**No.**	**Research Area**	**No.**
Operations Research MS [1]	94	Environmental Sciences	36
Computer Science IA [2]	85	Software Engineering	32
Water Resources	72	Management	25
Engineering Civil	51	Engineering Manufacturing	24
Engineering Industrial	48	Geosciences Multidisciplinary	23

[1] Management Science; [2] Interdisciplinary Applications.

Table 14. The top 10 contributing organizations in the field of S-O.

Author	Country	Publication	Author	Country	Publication
Indian Institute of Technology	India	17	North Carolina State University	China	9
National University of Singapore	Singapore	13	National Tsing Hua University	China	9
University of North Carolina	USA	11	Purdue University	USA	8
Virginia Polytechnic Institute State University	USA	10	Ohio State University	USA	8
Iran University Science Technology	Iran	10	Amirkabir University of Technology	Iran	8

5.1. Simulation-Based Optimization

This is the most popular S-O framework among the SC studies, where solution generation, function evaluation, surrogate modeling and mathematical model enhancement are among the major justifications for hybridization of the simulation model into an optimization process. The solution evaluation is basically formed around the black box concept and using simulation models as a function evaluation tool for the cases in which measurement using analytical approaches is not effective or feasible. Eleven out of 24 published simulation-based optimization papers belong to this category, where a simulation-based heuristic is proposed as a solution algorithm to solve complex mathematical problems. Such heuristics use simulation as a part of the algorithm to evaluate each individual in the population of solutions [109–111]. The study on logistics network design by Keizer et al. [112] is another example of this type, where simulation is incorporated into the model to simply assess the feasibility of the optimum solutions. J. He et al. [113] employed either case of evaluating and checking for the feasibility of the individual solutions by integrating the simulation into a genetic algorithm and particle swarm optimization to repair the unfeasible solutions and evaluate them, respectively. In another example, M-Torres [114] solved stochastic LRP using a simulation-based ant colony optimization algorithm. In his study, stochasticity is the major advantage of hybridization. The assessment of different solutions from the Pareto optimal set using simulation is another novel idea tested by Napalkova et al. [115]. Other papers gained the advantage of evaluating the optimal solutions in terms of the other measures, such as KPIs in sourcing by Ding et al. [116], and the qualitative measures, such as customer satisfaction in the design of inventory systems by Chu et al. [117]. In one recent relevant study, M. Gueller et al. [118] applied a multi-objective particle swarm optimization algorithm for the optimization of inventory decision variables (reorder point and order quantity), to be evaluated in an object-oriented simulator in terms of different performance measures such as customer service level and demand fulfillment rate, among others. In another related paper, Wang et al. [111] employed simulation in a transportation study to estimate the cost and reliability of solutions in a routing problem.

Using simulation runs to create a surrogate model and solving it via optimization techniques is a statistical-based approach that belongs to the simulation-based optimization category. This type of framework is studied in two SC research papers [119,120] that aimed at optimizing the inventory problems. The next category of solution generation aims at computing some of the variables based on the outcomes from the simulation runs. In the only paper of this type, Rooeinfar et al. [121] applied simulation to find the best routes, as well as dismissing the inefficient facilities in the SCN model. This category is the least common type among the S-O frameworks among the SC studies. However, it is logical that outsourcing of some of the decision variables can reduce the complexity of the mathematical model. Therefore, this last type of simulation-based optimization frameworks is best suited to reduce the complexities in the integrated mathematical models in the design of SCN.

Finally, the so-called analytic model enhancement deals with uncertainty in the mathematical models. Moreover, a reasonable approach in the optimization of SCN is selecting the control parameters of each entity through simulation runs. Generating more realistic solutions through the consideration of uncertainty belongs to the former function, which is addressed in [122–124]. These authors gained the advantage of using simulation within an algorithmic framework to produce more reliable solutions out of the optimization part. The sensitivity analysis method in the modeling of SC risk developed by Mizgier [125] is one of the most recent approaches that can be employed with the objective of analytic model enhancement. This approach can be employed to develop hybrid S-O frameworks to improve the analytical models of SCN in terms of risk and uncertainty. Parameter generation is the latter purpose of integrating simulation under this sub-category of simulation-based optimization frameworks that aim to mitigate the number of unnecessary assumptions in the analytic part, which in turn improves the quality and reliability of the optimum solutions. G. Merkuryeva et al. [126] proposed an optimization framework for the design of multi-echelon SCN, where the simulation part generates input data, to be stored and transferred to the optimization part via VBA (Visual Basic for Applications). This framework also allows one to easily switch from one policy to another in a user-friendly simulation environment. The other example of parameter generation is applied in the study on cold SCND by Saif et al. [127], where the authors selected the inventory parameters, such as reorder-point and ordering frequency/quantity using simulation runs within the optimization algorithm. Similarly, Diaz et al. [128] embedded simulation runs into the framework to remove the autocorrelation effects in the final results of a study on inventory systems. There are also some studies that aimed at the multiple purposes of integrating simulation into the framework. As an example, Singh et al. [129] applied an agent-based simulation model within a simulation-based optimization framework to serve as both an evaluator and estimator of cost as an input parameter in the optimization module.

5.2. Optimization-Based Simulation

The next major category, optimization-based simulation, is technically developed based on the idea of the optimization of the tuning parameters for each agent in an SCN. The contribution by Bodon et al. [130] is one of the first published papers in this regard, where the authors examined the method of coupling an optimization model with a simulation model to simultaneously optimize variables from different SC elements. Shwartz et al. [131] applied the same framework in the context of the semiconductor industry. Distinguishing optimization-based frameworks from simulation-based ones is not absolute. However, they are differentiated based on the logic behind hybridization. A common characteristic among the majority of the published papers in this category is optimization of controllable variables to be used as inputs in a simulation model. More particularly, applying agent-based simulation modeling as a powerful tool for optimization of SCN [132] and running an external optimizer to optimize the controllable parameters for the operation of each agent in the SC system (supplier, market, production site and distributer agent) are common practice in this field. A good example of this type is the study by Shahi et al. [133], which is placed in optimization-based simulation frameworks according to our categorization, although the authors termed it as a simulation-based approach. In another relevant study, Mele et al. [134] proposed the same idea by modelling the SC system in discrete-event simulation, where each entity is an agent. The model developed by Sahay et al. [135] also applied optimization inside a nested structure to optimize the variables of each participating agent in an SC system. The most recent framework of this type is applied by Zhang et al. [136] in the design of SCN for biofuels. Their simulation part identifies flows in the designed SCN by the optimization model, where cost minimization is the eventual objective of the framework.

An optimization-based simulation frame can also work recursively, where the optimization model is responsible for generating the input data to feed the simulation part and the simulation serves to assess the stopping criterion (according to Ko et al. [124]). This procedure might be continued up to the pre-determined performance measure point. The same recursive framework is applied for the re-configuration of an express delivery logistic network and logistics in a multi-echelon SC in studies by Kim et al. [137] and Hochmuth et al. [138], respectively. In some other studies of this type, the design of SCN is done through the optimization of decision variables from different SCM elements [106–108].

5.3. Simulation Optimization (Optimization of Simulation)

The last group of S-O frameworks, simulation optimization, generally focuses on improving the search parameters/procedure in the simulation studies where a variety of alternatives have to be simulated. These approaches include fractional factorial design in the design of experiments to avoid unnecessary runs and the evaluation of all of the possible alternatives. A most recent approach to this problem is simulation optimization, where an intelligent optimizer determines the proper number of runs and guides the simulation toward optimality. The framework developed by Sahay and Ierapetritou [9] is a good example of this type where the simulation runs would be terminated if and only if the difference among the cost values from the simulation model and the optimizer is less than a specific value. This type of S-O framework is mostly concerned with shortening the computation time by minimizing the number of alternatives to be evaluated, while also reducing the number of replications and simulation runs [139–141]. In an SCN study by Meisel et al. [142], a discrete event simulation is coupled with an optimizer to search for improved alternatives by means of a meta-heuristic algorithm. The framework proposed by Otamendi et al. [143] is another example of this type where a genetic algorithm is employed to reach the optimal solution out of the simulation runs within a satisfactory time.

Table 15 contains a brief explanation of the practical implications of applying S-O frameworks in the integrated SC optimization. In general, it has been attempted to reduce the complexity of the analytic part in the integrated problem mostly by the application of optimization-based simulation frameworks (i.e., converting to single objective optimization). On the other hand, the presence of inventory-related variables in the integrated problems can potentially increase the complexities of the models due to the periodic and nonlinearity functions. Moreover, the consideration of performance measures, such as KPI as a fitness function in the simulation part of the framework, can be quite helpful when the simultaneous inclusion of qualitative and quantitative measures is needed. It is worthwhile to mention that the random behavior of a system can be captured just through a simulation-based framework. Finally, it is shown that applications of S-O frameworks have enabled about 80 percent of the cases to work in a stochastic environment.

Table 15. S-O frameworks in integrated SC optimization.

Rank	Framework Type	Implication	# Papers
1	Optimization-based simulation	Optimization of the basic decision variables in the sub-systems considering the outcomes from the plenary simulation model that captures interactions and random behaviors in the system	8
2	Simulation-based optimization Solution generation	Outsourcing of one or more variables to a simulation model in order to reduce complexities in the optimization part and minimizing the process time	8
3	Simulation-based optimization Function evaluation	Calculation of fitness function for each individual solution for the cases that are difficult/not applicable to be calculated via the optimization part (i.e., quantitative, nonlinear); repairing the infeasible solutions	6
4	Simulation-based optimization Analytic model enhancement	Reduction in the number of assumptions in the analytic part by considering stochasticity in the estimation of the real-world parameters	4

6. Studies on Sustainability

According to the literature, the study on sustainability has been altered from an emerging topic to a growing one among both integrated mathematical models and S-O frameworks. Sustainability in the design of SCN demands the consideration of various factors across the economic, social and environmental pillars, and sustainability cannot be achieved unless the mentioned aspects are taken into consideration together. On the one hand, it is necessary to address social and the risk factors in SCN optimization of particular products. On the other hand, the environmental factors comprising air and noise pollution, congestion, wear and tear, among other factors, as well as the operating costs should be address simultaneously. Minimization of CO_2 emission as the major environmental factor has been addressed in a number of S-O studies. Saif et al. [127] proposed a concave minimization problem in the context of a cold SCN and developed a simulation-based optimization approach to solve it. Zhang et al. [136] employed a single objective mathematical problem within an optimization-based simulation framework to optimize the cost of CO_2 emissions alongside the other variable costs. Sahay et al. [9] coupled an agent-based simulation with an optimization problem in a simulation optimization study, while the carbon emission is restricted via a constraint in the mathematical part of the framework. The idea of calculating the fitness value of each individual optimal solution using KPIs after simulation runs is examined by Ding et al. [116]. This idea can be applied in further studies to cover a variety of the other sustainability indicators. In another possible approach, the given social and environmental restrictions can be fulfilled in the simulation part of S-O frameworks, while the cost criterion can be optimized through an external optimizer. Other studies have optimized the customer service level in addition to the variable costs [115,117,118,126,130]. In a simulation optimization framework developed by [143], the fitness function is calculated using a lexicographic structure where the individual optimum solutions are ranked based on total cost, customer service level and the average work in progress material. The model proposed by Shang et al. [144] can be categorized in the same group. They offered the only S-O approach where the simulation model is used to construct surrogate models and is then being optimized, while three levels for desirability are defined according to the customer service level. The other socio-environmental aspects of the sustainable design of SC, such as risk of population exposure, have not been addressed thus far. However and among the integrated problems, several LRP models worked on risk issues by minimizing population exposure around the facilities, as well as the transportation routes in the context of hazardous material. LIP models have been more concerned with customer service level and other responsiveness measures. Last of all, since IRP models are more popular among the studies on maritime shipping and vendor-managed inventory systems, they have been mostly dealing with environmental aspects of sustainability.

Resiliency in the design of SCN is another emerging topic that can be addressed through the application of S-O frameworks. Since disruptions are rare events, it is important to find efficient ways to quantify them. The proposed model by Mizgier et al. [5] is a good example of this type, where the authors attempted to measure the business disruption risk in the context of SCN, using Monte Carlo simulation. Such an approach can be coupled with a proper M-O optimization algorithm within a simulation-based optimization framework, in order to evaluate different solutions in the Pareto optimal set in terms of resiliency and risk measures.

7. Conclusions

Due to the limited features of the conventional mathematical modeling in the context of SC, the literature in this area is in the decline phase. The emergence of integrated mathematical modeling and S-O frameworks has been a response to this trend. According to the frequency analysis, S-O frameworks are transitioning from an emerging topic to a growing research area, while the integrated problems are likely to be saturated during the next few years. However, the LIP literature is expected to keep pace in the upcoming years.

Acknowledging sustainability as the major focus of the modern SC [12], the present systematic review shows that research on sustainability among the integrated mathematical problems is expanding rapidly. On the other hand and among the existing S-O frameworks, even though the inclusion of simulation models potentially simplifies the evaluation process on multi-criteria measures, such as sustainability and resiliency, this trend has not been sufficiently addressed yet. Owing to the fact that resiliency plays an influential factor in building sustainability, studies on this multi-criteria factor in SC is also awaiting further investigation. The S-O frameworks are expected to play the major role in the future of studies on sustainability and resiliency.

According to the bibliometric analysis, the simulation optimization papers (optimization of simulations) are mostly published in journals with the scope of simulation studies (i.e., Simulation Modelling Practice and Theory), while the articles on simulation-based optimization and optimization-based simulation approaches can be mainly found among the O.R. journals (European Journal of Operational Research, Computers Operations Research, among others). However, both of the mentioned topics have received the most contributions from the O.R. research area and the European Journal of Operational Research. Referring to the citation records, the most influential papers in each of the sub-categories are identified. It is shown that the scholars from the USA, China, Iran, Canada and France are the key contributors to the new generation of O.R. approaches in SC optimization.

Considering the subjective review of the literature and the bibliometric analysis, the S-O framework can either work as an alternative for the integrated mathematical models or as a solution approach to solve them. It is shown that the solution generation type of simulation-based optimization and optimization-based simulation frameworks are best suited as alternatives to the integrated problems to overcome the mentioned issues. Many of the conventional models in the literature would benefit from this trend by an upgrade to a simulation-based optimization framework of the mentioned types to overcome the inefficiencies in the model. By doing so, a number of decision variables can be outsourced to a simulation model, which in turn can reduce the computation time and complications in the coding procedure, while also incorporating stochasticity into the system. On the other hand, the integrated models mostly belong to the NP-hard class of problems, and it is expensive and time consuming to apply them in large-scale real-world cases. Likewise, due to the complexities in stochastic programming, most of the proposed models in this class are being applied in an isolated-deterministic environment. The main purpose of an S-O framework as a solution approach is to solve large-scale mathematical problems in a stochastic environment. According to the present review, analytic model enhancement and function evaluation types of simulation-based optimization frameworks are well suited to overcoming the complexities associated with solving large-scale, stochastic, multi-objective and nonlinear problems. The developed S-O solution algorithm to solve the stochastic LRP model by Herazo et al. [145] is the best example of this type. The simulation-based optimization approach developed by Montoya et al. [114] is another contribution that aims at solving an integrated model in a stochastic environment. Moreover, the simulation-based approaches can be helpful to adjust the components and parameters of an optimization algorithm. Due to the technical nature of this subject, contributions of this type are quite scarce among the SC studies. A framework of this type that has been applied in the context of the routing problem is the one developed by Merkuryeva et al. [145] where the improvement of the optimization algorithm in fitness landscape analysis is achieved through simulations. They proposed a new scheme that helps to select a proper optimization algorithm and determine the relevant algorithm parameters to enhance the efficiency of the selected algorithm.

As a reminder, the present study has suggested that any conventional mathematical problem can be upgraded to an S-O framework to address real-world problems while applying fewer assumptions. By so doing, the simplification of the mathematical component can facilitate the use of commercial solvers, like CPLEX and LINGO, which are far less complicated for applications in multidiscipline studies. The present review can assist in further empirical experiments to prove the main proposition of this study, i.e., that S-O frameworks are a viable alternative for integrated mathematical modeling. Such future research may empirically justify the hybridization of the previously-proposed mathematical models with simulation models to address quantitative measures in a stochastic environment. The present study is limited in the scope of the reviewed papers. A further review on this topic can be applied considering other databases (i.e., Scopus), as well as relevant conference papers.

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