Sustainable Factors for Supply Chain Network Design Under Uncertainty: A Literature Review

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Abstract. The concept of sustainability, which is considered three pillars covering the concept of economic, environmental, and social factors, has become an effectual attempt to increase competitiveness for institutions. Being sustainable in the supply chain enables enterprises to respond to increasing customer needs in the most appropriate way. Today, traditional supply chains are replaced by sustainable logistics network designs due to environmental and social requirements. In this study, considering the uncertainty situation, the studies carried out on closed loop supply chains that are formed as a result of integration of forward and reverse logistics as well as forward and reverse logistics by itself are examined on the basis of sustainability factors. Sustainability sub-factors are also included in this study. As a result of the research, brief explanations can be seen about sustainable supply chain network under the uncertainty covering all three sustainability factors and gaps in the literature are clarified for future research opportunities.

Keywords: Sustainability · Three pillars · Supply chain · Network design · Uncertainty

1 Introduction

Supply chain network design and management emerges as a research subject that is frequently discussed today, and its importance is increasing day by day. In line with the increasing consumer awareness and green logistics concept, companies are trying to develop strategic plans and environmentally sensitive systems. These systems: It covers all phases of the product from raw material procurement to consumption. In addition, the fact that these systems are very difficult to imitate due to their long-term plans enables companies to make a difference by providing a competitive advantage in the market. Businesses are looking for ways to respond to increasing consumer needs, to maintain their profitability and to gain competitive advantage, rather than differentiation in product and sales policies. In this context, efficiency in production, distribution and recycling processes should be ensured and logistics channels should work more systematically and in coordination. This is possible by managing the supply chain effectively. But effective management of the supply chain; It is quite difficult and complex in terms of the number and structure of its existing channels and the integration of new technologies.

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In its simplest definition, supply chain; It is the whole of logistics systems that covers the process of transforming raw materials into final products and/or services and delivering them to the end user. The control of material and information flow between suppliers, manufacturers, distributors, customers, and all other intermediary channels along the chain has created the term of supply chain management. Companies should analyse the market and competition conditions well and configure their supply chains to adapt to changing environmental conditions. Effective management of the supply chain is among the critical factors of sustainable success for companies in difficult economic and competitive conditions. Being sustainable in the supply chain will increase the success of companies in all activities as it will include many sub-processes from raw material supply to delivering the final product to demander. Sustainable supply chain management: In addition to providing economic competitive advantage to businesses, it is expressed as an approach that tries to add value to stakeholders at all stages of the chain in environmental and social dimensions [1].

With this approach, businesses try to increase all activities that will add value to the product or service throughout its movement in the chain. To achieve such developments, businesses need to lay out, design, work up and manage their whole supply chain with a sustainability manner by taking into consideration does not compromise the sustainability of involved players. This can only be possible by considering the sustainable supply chain factors together. The primary aim of most businesses is to try to minimize total chain cost or maximize total profit. In addition, businesses are trying to use their resources by developing environmentally sensitive systems with the effect of increasing consumer awareness and globalizing world. For a sustainable supply chain, it is not enough to consider only economic or environmental factors. Although the environmental dimension of sustainability is more prominent, it is possible to obtain more sustainable systems in supply chains where social factors are also addressed. Therefore, it is necessary to consider the concept of sustainability as a whole of economic, environmental and social factors, also known as the 'three pillars' of sustainability. Considering the factors together, it is shown in Fig. 1 that conflicting objectives can be defined under the same concept.

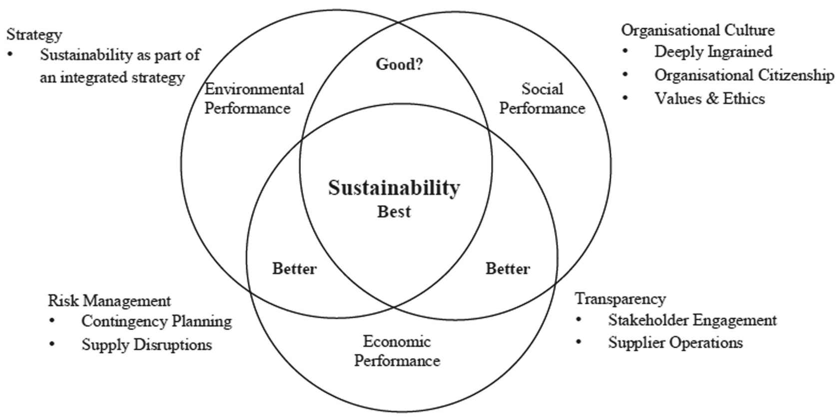

Fig. 1. Three pillars of sustainability [2]

By considering the factors together, the complexity of the problem increases when uncertainties such as demand in the supply chain and product return quantities are in question. However, today's optimization-based support systems and developments in information technologies make sustainable supply chain network designs possible.

2 Literature Review

It is possible to observe the economic dimension of sustainability in almost all studies from past to present studies on supply chain. In the objective functions of these studies, it is possible to frequently encounter models that minimize the total cost of the supply chain in question or maximize the total profit of the enterprise. It is frequently observed that the mathematical models in the studies are constructed in the deterministic model type in order to provide ease of solution. The stochastic approach is dominant in supply chain problems where there are uncertain quantities in parameters such as demand, return and waste quantities. The stochastic nature of the uncertainty has also been tried to be resolved with fuzzy or robust modelling logic. The number of objective functions varies depending on the number of sustainability factors of the supply chain studied. In general, studies that deal with a single dimension of sustainability such as economics are single objective, while studies that also consider environmental or social factors are multi-objective. The primary goal in supply chain problems is to optimize components such as delivery speed, costs, stock levels and production quantities. When the studies are examined in terms of solution methods, mostly optimization-based solution methods are used. In studies in which the optimization technique is used, a solution can be achieved in small-scale problem sizes. With the increase in complexity, optimization-based support systems are insufficient to solve the problem, especially in problem types that fall into the NP-hard class. For this reason, heuristic solution methods have been developed. Some of them used more than one metaheuristic method together in order to produce more effective solutions [3–6]. Apart from these, simulation-based solution methods are also used to solve the proposed models. An intelligent hybrid algorithm combining genetic algorithm and simulation solution methods has been designed [7]. In addition to the optimization solution methods, simulation techniques were used in the result display [8]. Moreover, simulation-based system dynamics optimization approach is also used under alternative scenarios in a closed-loop supply chains problem that reproduces [9].

Traditional supply chain problems mostly involve forward logistics activities. For these environments, the widely known standard mixed integer linear programming (MILP) approach was first developed by Mirchandani and Francis in 1989 [10]. At this time, a standard set of models for the concept of reverse logistics has not yet been established; however, a MILP model for recycling industrial by-products was developed by Spengler et al. in 1997 [11]. Afterwards, integrated studies including reverse flow activities were started in addition to forward logistics where production and distribution operations are carried out. These systems, which were first proposed by [12] in 2002 and formed as a result of the integration of forward and reverse logistics, are also called closed-loop supply chains. In this study, it has been shown that the most successful companies in reverse logistics are those that manage closed-loop supply chains that tie themselves tightly with forward supply chains. Closed-loop supply chain-themed studies, which include the economic dimension of sustainability, are frequently encountered in the literature. The increase in the understanding of environmental awareness has also increased the importance given to the concept of green supply chain management. The balance between the reduction of cost and preservation of environment has become an efficient initiative for businesses to increase their sustainable competitiveness. In this context, the studies in which the economic and environmental factors of sustainability in closed-loop supply chains are handled together are as shown in Table 1.

Table 1. Closed loop supply chains including environmental and economic factors

Paper	Model				Objective function		Methodology			Uncertainty
	Det.	Robust	Fuzzy	Sto.	Single	Multiple	Opt.	Heu.	Sim.	
13				*		*	*			*
14				*		*	*			*
15		*			*		*			*
16				*		*		*		*
17	*				*			*		
18	*					*	*			
19	*		*		*		*			*
20	*				*		*			
21	*					*	*			
22			*	*		*	*			*
23				*	*		*			*
24		*		*	*		*	*		*

Det.*: Deterministic, Sto.*: Stochastic, Opt.*: Optimization, Heu.*: Heuristic, Sim.*: Simulation

Judging by the studies mentioned in Table 1, an integration perspective is presented to develop a green and sustainable closed-loop supply chain network under uncertain demand [13]. In the stochastic programming model, two objectives are proposed for CO_2 emissions and total operating cost. The scenario-based method is suggested to represent the uncertain demand. A Lagrangian relaxation method was used to solve the model. He designed a closed-loop supply chain network [14] that considers sustainability dimensions and quantity discounts under uncertainty issues. For this purpose, a multi-objective stochastic optimization model is formulated for supplier selection and location-allocation-routing problem. The first and second objectives of the model seek to minimize total costs and environmental emission impacts, respectively. The third goal is to maximize the responsiveness of the proposed network. Also, the epsilon constraint method is used as a solution method. In order to produce robust closed-loop supply chain designs that reduce uncertainty and greenhouse gas emission burden, data-driven approaches have been proposed using ‘Big Data’ [15]. More specifically, a distributed robust optimization model (DRO) and an adaptive robust model (ARO) for the design of transport and locations of facilities for waste disposal of closed-loop supply chains to address multiple uncertainties (customers' expectations, demands, and uncertainties in recovery phase) have been developed. Historical data is used for both models based on uncertain parameters of previous periods to make robust decisions in next stages. The K-L divergence was included in the uncertain parameters to evaluate the value of the data. A two-stage multi-objective stochastic model for a closed-loop supply chain has been developed by considering risk, economic and environmental considerations simultaneously [16]. To solve the model, a series of memetic metaheuristics are taken into account. Also, the epsilon constraint approach was applied at small sizes to validate and solve the proposed framework of metaheuristic results. Virus Colony Search (VKS) and Keshtel Algorithm (KA) are adapted to the multi-objective model. Pareto optimal solutions were compared with four assessment metrics in different criteria. The purchase quantity, production costs, costs of allocating customers to distribution centers, demand and return rates are uncertain, and in addition, the rate of return depends on the customer's demand. In other words, the returned number of products to recovery centers is assumed to be a fraction of what customers demand. A green urban closed-loop logistics distribution network model that minimizes greenhouse gas emissions and total operating cost has been proposed [17]. Multi-objective Pareto optimization results were achieved. These results also show that the combination of transport vehicles, including electric and fuel types, can efficaciously provide a win-win strategy that includes costs of distribution and carbon emissions, which would be proper for businesses. In addition, this study contributes to the literature on the vehicle routing problem by providing the concept of using the closed-loop cooperative logistics distribution mode to promote green logistics development and optimize existing logistics distribution issues. Heuristic methods were used to solve the single-purpose model. Tabu search, ant colony and adaptive quantum ant colony algorithms were designed to examine the results comparatively. [18] suggested a multi-stage, multi-product and multi-objective mixed integer linear programming model aimed at designing and planning a forward and reverse green logistics network. The primary goal here is to minimize processes, operating, transportation costs, and fixed costs of plant. Minimizing the amount of CO_2 emissions based on grams appeared as the second objective. The third objective is to optimize the number of machines in the production line. The proposed model has been validated by applying it to the white goods industry with a few test problems. From the solution methodology perspective, to obtain set of pareto solutions, the epsilon constraint method is developed. In the multi-product circular closed-loop supply chain, Fuzzy Analytic Network Process (FANP), Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL) and multi-objective mixed integer linear programming models have been established [19]. For order allocation and circular supplier selection, a hybrid approach has been developed considering the multi-depot, capacity green vehicle routing problem using heterogeneous vehicles. A fuzzy solution approach is proposed to convert the multi-objective model containing demand uncertainty into a single-objective one. The model has been applied to the automobile timing belt manufacturer to demonstrate the applicable side of the suggested model in real world applications. Balance between environmental and operational performance measures of shipping products of a closed-loop supply chain network problem were examined [20]. To formulate the model linear programming method is used that strikes the balance between several costs, including transportation of goods and emissions in the chain. The solution results are presented for several scenarios using a realistic network example. A multi-objective mixed integer linear programming model is presented for sustainable supply chain design that takes into consideration the principles of Life Cycle Assessment (LCA) and the traditional material balance constraints in the supply chain at each node [21]. Here, gas emissions from various production processes and transport systems, solid and liquid wastes are separated from each other. Some numerical scenarios are derived randomly for parameters and constraints to shoe the practical solvability of the model. Fuzzy – stochastic modelling approach is used in [22] to deal with different types of uncertainty. Considering to the network flexibility, the balance between the economic and environmental performance is tried to be set. Carbon emission is used to measure the environmental performance. Pareto optimal solution is obtained with sample average approximation based weighting method. In [23], which examines demand uncertainty, deals with retail market configurations. Two-stage stochastic program is used as a modelling approach. L-shaped algorithm is used as a solution methodology. Carbon emission is considered as environmental impacts of sustainable closed loop supply chain. Sensitivity analyses are available according to different policies and provide some managerial implications. A study conducted recently [24] examined reverse logistics in a closed-loop supply chain by developing a robust stochastic-based optimization model. Chance constraint method is used in this study to deal with the stochastic nature of the problem. Obtained results are compared with the proposed heuristic algorithm. A real-life case study in the automobile industry is applied considering to the carbon tax policy as an environmental impact of the supply chain. In summary, as it can be understood from Table 1, in cases where uncertainty is ignored, deterministic modelling approach is emphasized. The environmental and economic factors of sustainability have been examined for two purposes as well as combined for a single purpose. Optimization methods are frequently used as a solution technique. Customer demands, product return quantities and therefore uncertainties in model parameters are handled with robust, fuzzy, or stochastic modelling approaches.

In some studies, in the literature, it is possible to come across logistics network designs that are only forward or only reverse, with a more specific approach rather than a closed-loop supply chain. However, due to the stochastic reverse flow of products, the inconsistent quality of used products, and the variation in prices of remanufactured and recycled products, designing a reverse logistics system has become more complex in comparison to a forward logistics network. Therefore, studies done about reverse logistics network design have increased tremendously in recent years. If we look at some of these studies, the uncertainty situation in reverse logistics network designs, which includes the economic and environmental factors of sustainability, has been investigated with the multi-objective stochastic modelling approach [25, 26]. Here, optimization techniques such as sampling average approximation procedure and epsilon constraint method were used as solution methods. A scenario-based approach is used to handle with stochastic parameters. In reverse logistics network design, environmental and economic factors including uncertainty [27] are examined in a single objective deterministic model [28] with a stochastic approach. Apart from these, a multi-objective deterministic model that includes uncertainty in parameters such as distance, demand and cost and advanced supply chain planning [7] has used from simulation and heuristic techniques in the solution method. When looking at the forward logistics network design that considers the economic and environmental factors, [29] proposed a multi objective sustainable mathematical model for designing a bioenergy supply chain network. In addition to the economic and environmental factors, water and energy are also regarded as sustainability sources in this study. Geographic Information System (GIS) technique and goal programming method are used to solve the proposed model. To obtain a green and resilient supply chain, [30] proposed a robust multi objective optimization model. Heuristic techniques are used in the solution methodology. Economic and environmental factors are considered in the supply chain consisting of suppliers, manufacturers, and warehouses. A multi objective forward logistics network model is proposed with using robust mathematical modelling approach to address of economic and environmental factors of sustainability under uncertainty in [31]. To obtain pareto optimal solutions, epsilon constraint method is used.

In all the studies mentioned above, social factors were not considered; however, when it comes to sustainability, economic, environmental, and social factors should be examined simultaneously. The studies in which the 3 pillars of sustainability are examined together are as shown in Table 2.

Table 2. Supply chains including environmental, economic and social factors

Paper	Model				Objective function		Methodology			Logistics		Uncertainty
	Det.	Robust	Fuzzy	Sto.	Single	Mult.	Opt.	Heu.	Sim.	Forw.	Reverse	
5	*					*		*		*	*	
6	*					*		*		*	*	
32	*					*	*			*	*	
33	*					*	*			*	*	
34				*		*	*				*	*
35				*		*	*				*	*
36			*			*	*				*	*
37			*			*		*			*	*
38		*				*	*			*		*
39		*				*	*			*		*
40		*				*	*			*		*
41			*			*	*			*		*
42	*			*		*	*			*	*	*
44	*					*		*		*		

Det.*: Deterministic, Sto.*: Stochastic, Mult.*: Multiple, Opt.*: Optimization, Heu.*: Heuristic, Sim.*: Simulation, Forw.*: Forward

In Table 2, it is possible to see the studies in which only forward, only reverse or both are integrated in terms of logistics. Here, more emphasis is placed on robust, fuzzy, and stochastic models, since the three pillars of sustainability are examined together and systems that are more suitable for real life are in question. The number of established deterministic models is relatively less compared to Table 1. All models show a multi-objective function structure. Optimization techniques are mostly used in solution methods. If we look at the closed-loop supply chain studies, [5, 6], who used the deterministic modelling approach because there was no uncertainty, used from heuristic techniques in solution methods, while [26, 27] used from optimization techniques. While [34, 35] includes stochastic models, [36, 37] used fuzzy modelling techniques only in reverse logistics network designs with uncertainty. In terms of solution method, unlike other reverse logistics network designs, [37] has used from heuristic methods. Robust modelling techniques have been used [38–40] for forward logistics network designs with uncertainty. [41], which developed an interactive approach depending on two-phase stochastic programming and fuzzy probabilistic multi-objective programming, used optimization techniques in the solution method to overcome the problems related to uncertainties in demand, cost and capacity. As can be seen, it is possible to encounter uncertainty in studies involving only forward or reverse logistics network design; however, uncertainty was examined in only one of the studies in which forward and reverse logistics were integrated [42]. This study presents a decision support tool called as ToBLoOM – Triple Bottom Line Optimization Modelling for the design of a sustainable supply chain. A general multi-objective mixed integer linear programming model has been established that combines interdependent strategic and tactical decisions. Strategic decisions; facility location and allocation, capacity decisions, supplier and technology selections, transportation networks including both single and intermodal alternatives. Tactical decisions; procurement planning, purchasing levels, product recovery and remanufacturing. Demand uncertainty is also analysed with a stochastic approach in this study. The three pillars of sustainability are addressed with the multipurpose programming method. The economic dimension is measured in Net Present Value (NPV). Environmental impacts during the establishment of the factory, production and remanufacturing transportation are reduced with the LCA methodology ReCiPe [43]. The social dimension is measured by a socio-economic indicator implemented by the European Union as the Sustainability Development Strategy - Gross Domestic Product (GDP). The deterministic solution is defined as the assumed worst-case scenario in terms of economic performance. For more realistic solutions, stochastic objective functions are obtained by adding stochastic approach to some decision variables in the deterministic model by performing scenario analysis. An application study was conducted for a European-based company with markets in Europe and South America. This study makes a major contribution to the literature by emphasizing the various research gaps needed with an integrated method that allows simultaneous evaluation of particular interactive decisions in the closed-loop supply chain. [44] proposed a multi-objective mathematical model that examines forward logistics between suppliers, manufacturers, distributor centers and customers. Heuristic techniques are used in the solution of the proposed model. Artificial bee colony algorithm has been modified and adapted to the problem.

3 Sub-factors of Sustainability

When sustainable supply chains are managed with the right strategic decisions, they will have various benefits for all members of the chain from beginning to end, including customers. With a correct planning, the deadlines of the enterprises will be shortened, waste will be reduced, costs will be reduced, and employee satisfaction will increase by providing better working conditions. In addition, increasing business reputation will provide a competitive advantage to the members in the chain. Apart from the benefits of sustainable supply chains to businesses and chain members, it is also of great importance with its sensitivity to the environment. In today's conditions, much more attention should be paid to the protection of natural resources and to ensure their conscious consumption. In recent years, studies that focus on environmental factors as well as the economic dimension of sustainability proves this. With increasing consumer awareness, customers have become more sensitive to environmental and social factors. Considering these factors, "environmental, economic and social" factors should be considered together to increase the benefits of the sustainable supply chain. As stated in Table 2, studies that deal with these factors simultaneously are as stated in Table 3 based on sustainability sub-factors.

As can be understood from the Table 3, LCA methods were used to evaluate the environmental effects of sustainability in [5]. The ReCipe method, which is used to convert long life cycle inventory results into a limited number of indicator points, is discussed in [33, 38, 42]. On the other hand, Eco-Indicator 99, the damage-oriented method of LCA, has been used in the analysis of environmental effects in supply chains [33, 34, 37]. Unconscious industrialization and the reduction of green areas, fossil fuel consumption and uncontrolled population growth are among the reasons that increase CO_2 emissions. Therefore, while analysing environmental factors [35, 39, 41] CO_2 emission was used. While examining the environmental impacts, [44] based on unit and fixed costs; [6] also discussed the environmental benefits and harms that result from the use of end-of-life products. [32] tried to minimize the total amount of fuel consumed. Economic factors in the studies; It has been tried to be resolved by performing cost, NPV and profit analysis. Social factors, on the other hand, have been expanded by differentiating according to the type of problem studied. Some of these are customer service levels, GDP, job opportunities and losses, working conditions and social life cycle analysis. Furthermore, seven focal subjects included in IS0 26000 covered as social responsibility dimension in [40]. Apart from that, making use of multi-criteria solution methods in his problem [36]; He examined environmental, economic, and social factors based on criteria.

Table 3. Sustainability sub-factors

Paper	Factors			Uncertainty
	Environmental	Economic	Social	
5	LCA	Cost	Job opportunities, losses	

(*continued*)

Table 3. (*continued*)

Paper	Factors			Uncertainty
	Environmental	Economic	Social	
6	Environmental benefits, harms	Cost	Job opportunities, worker safety	
32	Energy consumption	Profit	Customer service level	
33	LCA/ReCipe, Eco-Indicator 99, CML 2002	Cost	Social benefit indicator	
34	YDA/Eco-Indicator 99	Cost	Customer service level	Demand, waste
35	CO_2 emissions	Expected profit	Job opportunities, losses	Parameter
36	Environmental criteria	Economic criteria	Social criteria	Qualitative inputs
37	LCA/Eco-Indicator 99	NPV	Job opportunities, losses	Parameter
38	LCA/ReCipe	Cost	SLCA	Parameter
39	CO_2 emissions	Cost	Unemployment, migration, traffic congestion	Demand, cost
40	Water footprint, CO_2 footprint	Profit	ISO 26000	Parameter
41	CO_2 emissions	Cost	Working conditions, social commitments	Demand, cost, capacity
42	YDA/ReCipe	NPV	GDP	Demand
44	Environmental effects	Cost	Customer service level	

SLCA*: Social Life Cycle Analysis

4 Conclusions and Future Research Directions

In this study, peer-reviewed articles published in SCI indexed journals in the last decades in the scope of supply chain network design including sustainability factors under uncertainty are examined. In this context, closed-loop supply chain models that include the economic and environmental factors of sustainability and selected studies that include forward, reverse or closed-loop supply chain models that include the three pillars of sustainability are examined. The authors review studies about sustainable supply chain network design in the literature in six categories: sustainability factors, types of the model, objective functions, solution methodologies, direction of the logistic and uncertainty issues. While sustainability factors are classified as economic, environmental, and social factors, types of models are also considered as deterministic, robust, fuzzy and stochastic approaches. Studies that deal with the objective function as single or multiple are included. Studies that develop an optimization, heuristic or simulation-based solution approach are also included. In addition, the logistics aspect of the studies is examined as forward, reverse or closed-loop supply chains. It was considered whether the studies included uncertainty or not. Papers published in international journals among electronic bibliographic sources such as Scopus, Web of Science and Science Direct were searched using different keywords.

Referring to the studies in the literature, uncertainty factors which are examined according to the structure of the model established in studies involving uncertainty also vary. In addition, it is seen that some uncertainties, which change in the real world due to their nature in the real world, are examined in the parameters of demand and therefore product return, waste amounts, some costs and system constraints. However, the fact that there has not yet been a general study in this field, rather than problem-specific, about the research that deals with sustainability factors and situations involving uncertainty at the same time indicates that there is a gap in the literature.

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