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Supply Chain Sustainability Assessment using Hybrid Simulation-Optimization Modeling

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Abstract

The sustainability of the supply chain can provide organizations with a competitive advantage from economic, environmental and social perspectives. Therefore, the present study has tried to design a hybrid discrete event agent-based simulation model combined with meta-heuristic methods based on the simulation-optimization approach to evaluate the supply chain sustainability. Besides, it has been sought to improve economic, environmental and social objectives of the supply chain simultaneously to increase sustainability. The agent-based modeling was used to implement the supply chain components, while the discrete event simulation approach was used to implement production lines complexities. After the validation of the hybrid simulation model, the optimal/near-optimal values of the components influencing the sustainability of the supply chain were extracted by combining meta-heuristic algorithms with the hybrid simulation model. Note that the fuzzy Delphi method was used to quantify the effect of social components on supply chain performance. To implement the proposed model, the supply chain of one of the main entities in Iran's ventilation industry was chosen as a case study. According to the research findings, the use of the hybrid simulation optimization approach makes it possible to reflect all the supply chain complexities. Moreover, the integrated study of economic, environmental and social dimensions and the extraction of optimal/near-optimal values of the influencing variables using the combination of hybrid simulation model and meta-heuristic algorithms in the supply chain under study resulted in a near-zero waiting time for customers to receive products, an increase of 60,000,000,000 Rials in manufacturer's liquidity, the improvement in the status of products inventory maintenance to respond to fluctuations, and a 25%-increase in the objective function value.

Keywords: *sustainable supply chain management, agent-based modeling, simulation-optimization approach.*

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1. Introduction

In the last decades, research has been done on supply chains. Before environmental and social concerns were widely proposed, the supply chain management was limited to the effectiveness and responsiveness of a system in terms of supplying raw materials, applying production methods, and delivering products to customers [17]. However, regarding the shortage of resources and raw materials and environmental and social problems in the supply chain, some researchers suggested that a new generation of supply chain management should be created, with great emphasis on the

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environmental and social aspects of the supply chain [2]. Accordingly, numerous studies focusing on the supply chain sustainability were conducted [3, 4].

Sustainable supply chain management focuses on the integration of economic, social and environmental goals in the supply chain [14]. This concept, if implemented in the supply chain, leads to the creation of a sustainable competitive advantage in the market [35]. In order to achieve competitive advantages, it is necessary to look at all three dimensions of the sustainable supply chain in an integrated manner and optimize them [42]. However, due to the existence of random events and various uncertainties in today's supply chains, the use of traditional and analytical tools is no longer sufficient [39]. In recent research, supply chains have been analyzed using various tools such as mathematical modeling [40, 18], meta-heuristic methods [21, 13], simulation [16, 34] and simulation-optimization [29, 36].

Simulation, as an effective tool in the analysis of probabilistic systems, makes it possible to evaluate the dynamic behavior of the systems [45]. In addition, simulation is one of the most effective tools in supply chain evaluation and efficiency analysis due to its ability to deal with uncertainties and probabilistic events [25]. In general, there are three approaches of discrete-event simulation, dynamic systems and agent-based, each of which is specific to certain problems with different levels of detail [6].

In recent years, the combined use of these approaches in operations research and optimization has been highly attended by researchers. Researchers have also used the hybrid modeling approach in supply chain analysis, so that about 19% of the research based on the hybrid simulation approach has been carried out in the field of supply chain and logistics [7].

As far as we know and according to the literature, researchers have not used the hybrid simulation and optimization with meta-heuristic algorithms (simulation-optimization approach) to check the sustainability of the supply chain. This research aims to optimize the sustainable supply chain indicators by designing a hybrid discrete event agent-based simulation model of a supply chain, using meta-heuristic algorithms. In order to evaluate the hybrid simulation-optimization approach in this research, the sustainability of the supply chain of a company active in the ventilation industry is investigated.

The ventilation industry in Iran has experienced significant fluctuations due to problems such as international sanctions, price fluctuations, difficulties in the supply of raw materials, logistics cost fluctuations, manpower challenges, and energy restrictions.

The main objectives of this research are:

- Designing a hybrid discrete-event-agent-based simulation model to evaluate the supply chain in terms of economic, environmental and social objectives
- Utilizing meta-heuristic methods to extract optimal/near-optimal values of variables affecting the economic, environmental and social aspects of the supply chain and increasing its sustainability.
- Evaluating the hybrid simulation-optimization approach designed to evaluate the sustainability of the ventilation industry supply chain
- Evaluating the impact of changes in the ordering levels and environmental and social variables on the sustainability of the ventilation industry supply chain.

The research background is presented below. In the third section, the research methodology is presented. The research findings are provided in the fourth section. Finally, the conclusion and suggestions for future research are presented

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2. Research background

2.1. Theoretical background

2.1.1. Sustainable supply chain management

Sustainable supply chain management is a clear and strategic integration of economic, environmental and social goals of organizations. This approach helps managers formulate strategies for the organization's survival and success on a long-term time horizon [14]. Various models have been presented to investigate the sustainable supply chain, such as the analysis of political, economic, social and technological factors (PEST) [31], the triple bottom line (TBL) framework [12] and house of sustainable supply chain management model [44].

In this research, to formulate a conceptual model of sustainable supply chain, the house of sustainable supply chain model, as introduced by Teuteberg & Wittstruck 2010, is used. In this model, there are three social, economic and environmental pillars to keep the building balanced. Based on this model, risks must be identified and removed to obtain resources and achieve long-term profits. Figure 1 represents the house of sustainable supply chain model.

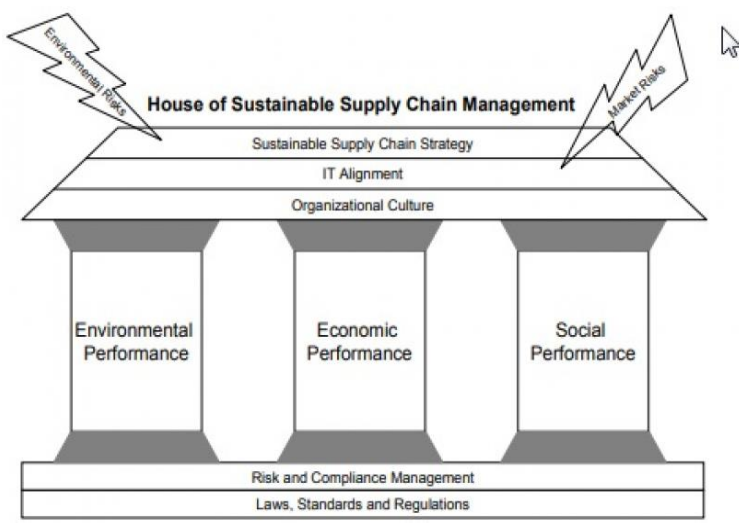

Figure 1. House of sSCM

2.1.2. Discrete-event simulation

Discrete-event simulation is the imitation of events happening in a discrete time period. This approach is suitable for problems whose formulation requires a high level of detail, and therefore a high volume of data and accurate estimation of the performance of the system components are necessary [22]. Discrete event simulation approach is used for the modeling at an operational level. This approach is adopted in many systems, including manufacturing and production systems [26]. In this method, the flow of entities occurs through blocks of activities, delays, queues, processing, and the use and release of resources [11].

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2.1.3. Agent-based modeling

In a system with dynamic processes and time dependence, it is possible to use agent-based modeling. Agent-based modeling consists of three main components [32]:

1. Agents and their behavioral characteristics
2. Methods of interactions and communication
3. Environment

Unlike the discrete-event simulation, the agent-based modeling has a bottom-up approach, in which a wide range of problems with different levels of detail can be modeled [6].

2.1.4. Simulation-optimization approach

The simulation-optimization approach is one of the optimization techniques for random and probabilistic parametric problems [36]. In this approach, by developing the simulation model of the system under study, the connection between the simulation model and meta-heuristic algorithms is established. The meta-heuristic algorithm tries to optimize the objective function by searching for different values of decision variables. This process is repetitive and is stopped based on conditions such as the number of repetitions or the impossibility of improving the obtained optimal solution. The simulation-optimization approach is shown in Figure 2.

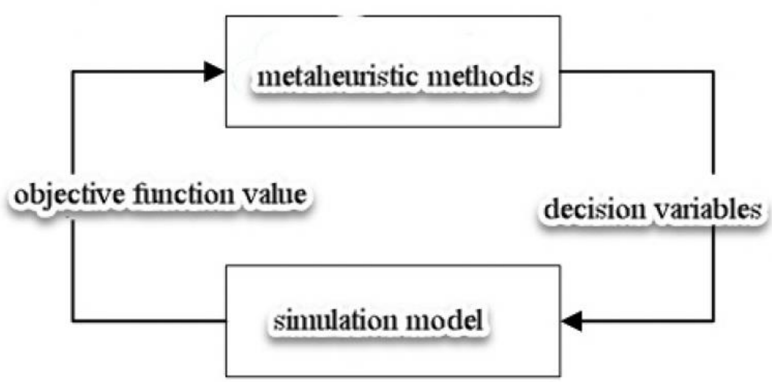

Figure 2. Simulation-optimization approach

2.1.5. Fuzzy Delphi method

Delphi method is one of the methods of group knowledge acquisition. In this method, the respondents do not know each other, which ensures overcoming group barriers [30]. Using fuzzy numbers in this method is called fuzzy Delphi. Fuzzy sets have the advantage of being more compatible with human linguistic and sometimes ambiguous descriptions. The fuzzy Delphi algorithm includes the following steps:

- Identification of a proper spectrum for fuzzification of linguistic expressions
- Fuzzy accumulation of fuzzified values
- De-fuzzification
- Choice of threshold and screening criteria.

In this research, due to the challenging process of quantifying social variables and determining their impact on supply chain performance, the fuzzy Delphi method has been used.

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2.2. Experimental background

In this section, the research conducted in the last five years on supply chain sustainability and sustainable supply chain management is presented. Jabbarzadeh et al. (2018) examined the sustainability of the supply chain with the aim of minimizing supply chain costs and maximizing its sustainability [8]. For optimization, multi-objective mathematical modeling was used. The research was a case study in the field of plastic pipe production industry. Fakhrzad and Gudarzian (2019) modeled the sustainability of the supply chain with the aim of minimizing costs, minimizing carbon emissions, and minimizing the delay in meeting customer demand using fuzzy multi-objective mixed integer programming [27]. In a similar research, Abeer et al. (2020) investigated the sustainability of the closed-loop supply chain with the aim of minimizing costs, minimizing carbon emissions, and maximizing the sustainability of the supply chain by meeting customer demand as much as possible [3]. In their research, genetic algorithm was used for optimization. Ahranjani et al. (2020) used mixed integer programming to design, program and investigate the sustainability of the bioethanol supply network with several raw materials [33]. The goals considered in this research were the minimization of costs and greenhouse gas emissions. Hosseini Mutlaq et al. (2020) developed a multi-objective mathematical model for designing a resilient and sustainable electricity supply chain network [41]. Minimizing the costs, minimizing the measures that reduce the resilience of the organization and maximizing the social responsibility aspects of the organization have been among the goals of this research. Nosrati and Arshadhi Khamse (2020) developed a two-stage stochastic planning model for the design of the supply chain with the two goals of maximizing sustainability and minimizing costs with regard to the cost of the penalty for unauthorized carbon emissions [28]. Considering the use of non-linear mixed integer programming approach, two methods of epsilon constraint and non-dominated sorting genetic algorithm have been used to solve the model. Tirkali et al. (2020) investigated a three-level supply chain consisting of suppliers, central warehouses and wholesalers to maximize the sustainability of the supply chain and minimize costs [11]. The case study of this research was in the supply chain of lamps, and balanced ideal planning was used for optimization. In order to evaluate the sustainability of the refinery supply chain, Wang et al. (2020) used scenarios such as increased demand, disruption in refineries, and interruption of transmission lines and utilized Monte Carlo simulation to examine the supply chain [37]. Govindan and Gholizadeh (2021) modeled a sustainable reverse logistics network with the characteristic of Big Data and the possibility of facility disruption using the cross-entropy algorithm and robust optimization [20]. Supply chain resilience based on strategic and tactical decision-making levels was investigated in a research by Sazvar et al. (2021) [38]. In this research, robust fuzzy optimization has been used to deal with uncertainties and optimize the problem, and influenza vaccine supply chain was considered as a case study. Amirian et al. (2022) presented a non-linear mixed integer programming model for the problem of sustainable supply chain network design and used the normalized constraint method to solve the multi-objective optimization problem and find Pareto optimal solutions [1]. Taleizadeh et al. (2022), taking into account supply chain resilience factors and using the Stackelberg game model with government leadership and producer followership, investigated the impact of tax rates on the fulfillment of the government's environmental and social obligations [43]. Farmarzi et al. (2023) reviewed the research conducted on the application of meta-heuristic methods to examine supply chain sustainability [15]. This review showed that in recent research, there is a tendency to use a combination of meta-heuristic methods more than traditional methods, which indicates the complexity of the dimensions of supply chain sustainability and the need to use more flexible approaches. Koi et al. (2023) examined the importance of choosing sustainable suppliers in the supply chain [10]. In their research, the choice of suppliers is assumed to have a direct effect on the stability of the supply chain. To evaluate the importance of this index, a combination of fuzzy sets and Bayesian network was used.

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A review of the literature showed that the majority of studies on supply chain sustainability used mathematical modeling and meta-heuristic methods, while the use of hybrid simulation-optimization to simultaneously examine economic, environmental and social dimensions in the supply chain was neglected. Accordingly, this research aims to cover this identified research gap.

3. Methodology

In this research, a 5-level supply chain comprising suppliers, manufacturers, distributors, retailers and customers is used to evaluate sustainability. Based on the definitions provided by Makal et al. [32], suppliers, manufacturers, distributors, retailers, customers, and vehicles are considered as agents that form the agent-based simulation model. The following figure shows the interactions between the said agents.

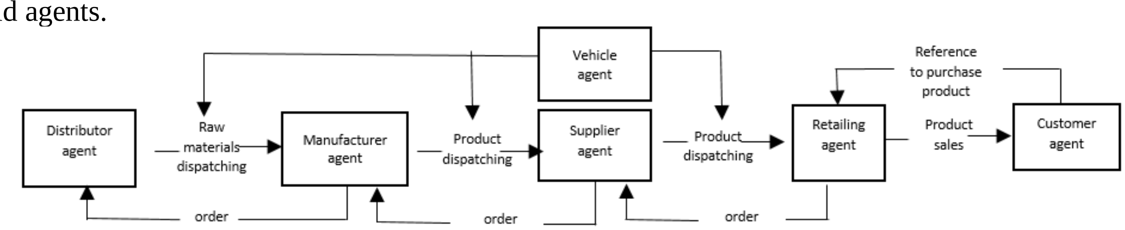

Figure 3. Interaction of supply chain agents

In the following, the features of each of the mentioned agents are presented.

3.1. Supplier agent

The supply of raw materials will be done by the suppliers. Based on the order received from the factory agent, this agent sends raw materials in the requested amount. The suppliers manage the logistics processes of sending raw materials by calling the vehicles agent.

3.2. Manufacturer agent

After receiving the raw materials from suppliers, the production of products begins in the manufacturer. The manufacturer uses the (s, S) policy to adjust the inventory and order points. Therefore, if the inventory of each of the raw materials is less than s, the manufacturer places an order with the suppliers until the inventory reaches S. It should be noted that if there are enough raw materials according to the consumption factor of each product, a product will be produced by the agent manufacturer. Due to the need to consider the details of production in this agent and the modeling at the operational level, the behavior of the manufacturer agent is modeled using the discrete-event simulation approach. The discrete event algorithm of production lines is presented in Figure 4.

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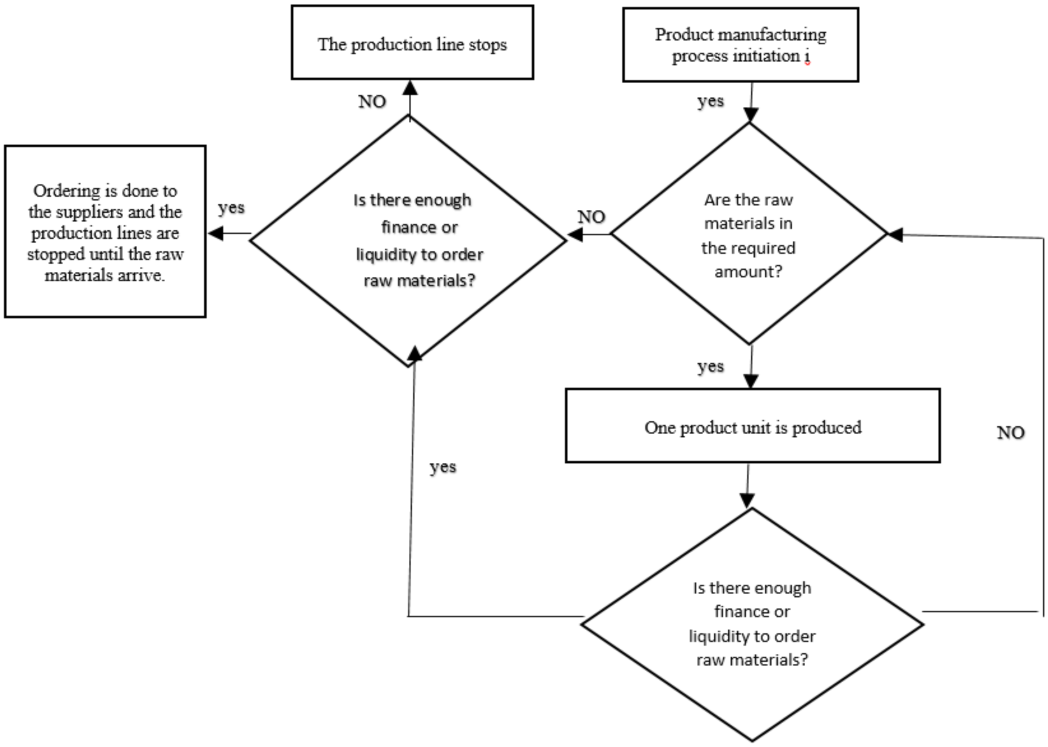

Figure 4. Discrete event algorithm of the production lines of the manufacturer agent

It should be noted that uncertainties such as raw material cost fluctuations and raw material delivery time fluctuations are included in the simulation model.

3.3. Distributor

According to the inventory control policy (s, S) similar to that of the manufacturer, the distributor agent orders various products to the manufacturer agent. Products are sent from the manufacturer to the distributors by the vehicles. Then the distributor agent provides different products depending on the order of the retailer agent. Shipping of products to the retailers is done by the vehicles.

3.4. Retailers

Distribution of products to customers is done by retailers. Similar to manufacturers and distributors, this agent has an inventory control policy (s, S) and receives its inventory from distributors. When the retailer receives the order from the customer, if the desired product is available, the retailer processes the order and presents it to the customer. If the stock is unavailable, the order will be kept until the stock arrives.

3.5. Customers

Customers receive their desired products by referring to retailers. Customer demand is determined by the probability distribution function and the selection of retailers to buy the required product is also random.

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3.6. Vehicles

The vehicle agent is responsible for transporting raw materials or products to the specified agent. At the time of receiving the order, this agent stores the product ID, the raw material ID, the specified amount, the ordering agent, and the geographic longitude and latitude of the ordering agent. Vehicles are initially in “ready” mode. After receiving the order, they change the mode to “moving”. At the time of reaching the destination, the agent’s status changes to “arriving at the destination”. In this step, the desired cargo is delivered to the specified agent.

3.7. Location and routing of agents by GIS maps

One of the capabilities of agent-based modeling in AnyLogic software is the possibility of combining agent-based simulation model with OSM server and GIS map data. This feature makes it possible to define the location of agents based on latitude and longitude and to match the distances between them to reality. It is also possible to use routing algorithms such as Dijkstra to guide the vehicle agent from one position to another. This feature has been used in this study.

3.8. Implementation of the hybrid simulation approach in the ventilation industry supply chain

To evaluate the designed hybrid simulation model, the supply chain of a company active in the ventilation industry is considered as a case study. In this supply chain, two products, burner and radiator, are produced. The burner production line consists of 4 casting stations, body assembly, final assembly, and packaging, and the radiator production line consists of 6 casting, grinding, polishing, assembly, paint, and packaging stations. Modeling has been developed using discrete event simulation in the manufacturer agent. The service time of each of the mentioned stations has been entered into the model using time measurement and probability distribution function fitting. The supply chain of this company has 12 suppliers in Tehran, Mallard, Safadasht and Shams-Abad. Some required parts are also supplied from abroad. 10 distributors and 20 retailers also play a role in this chain. Customer demand is also entered into the simulation model by using the data available in the system and fitting the probability distribution function.

3.9. How to consider economic, environmental and social dimensions in the supply chain of ventilation industry

Keeping raw materials and products in the supply chain has economic aspects. In case of maintaining excessive inventory, maintenance costs are imposed on the chain, and in case of keeping less than the required amount, shortage costs and delays in meeting the demand are entered into the system. Therefore, one of the goals of this research is to optimize the ordering point and the maximum amount of inventory maintenance, which is synonymous with the two levels s and S in the inventory control policy described in agent’s manufacturer, distributors, and retailers. Determining the amount of these levels has a direct impact on the profitability of the supply chain and increasing its sustainability.

Regarding the environmental aspect of this chain, in order to reduce pollutants from the production process in the manufacturer, special filters are used, which need to be replaced after producing a certain number of radiators and burners. Fines are also paid for environmental pollution. The cost of replacing filters and paying environmental fines will be deducted from the income of the chain and will have a direct impact on the overall performance of the supply chain.

In order to investigate the impact of social aspects on supply chain performance, by interviewing experts and considering the cost of each social measure, the following social indicators were finally identified:

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- Providing bonuses to personnel to increase work motivation
- Holding training courses to increase individual abilities
- Providing of welfare facilities for personnel

In order to evaluate the impact of each of the identified factors on the increase in production, the triangular five-point fuzzy spectrum has been used and the relevant ranges have been finalized based on the experts' opinions (Table 1).

Table 1. Triangular fuzzy numbers used to collect experts' opinions

Triangular fuzzy number	Title
(0, 0, 0.02)	very low
(0, 0.02, 0.1)	Low
(0.02, 0.1, 0.12)	medium
(0.1, 0.12, 0.15)	high
(0.12, 0.15, 0.2)	very high

In order to evaluate the impact of each of the three identified social indicators, the opinions of 20 experts in the ventilation industry were collected regarding the impact of each of the social indicators on the percentage increase in the production of the manufacturer's product. It should be noted that due to the dependence of each of the identified social indicators on the allocated budget, three scenarios with specific budgets have been considered. The relevant results are shown in Table 2.

Table 2. The results of collecting experts' opinions regarding the impact of social indicators

Social component		Fuzzy average comments on the impact of the social dimension on the production rate of the manufacturer	Final de-fuzzification number
The first scenario	Providing bonuses to personnel to increase work motivation	(0.112, 0.052, 0.009)	0.058
	Holding training courses to increase individual abilities	(0.053, 0.032, 0.011)	0.032
	Creating welfare facilities for personnel	(0.03, 0.021, 0.011)	0.021
The second scenario	Providing bonuses to personnel to increase work motivation	(0.0196, 0.044, 0.013)	0.084
	Holding training courses to increase individual abilities	(0.061, 0.039, 0.023)	0.041
	Creating welfare facilities for personnel	(0.083, 0.042, 0.021)	0.049
The third scenario	Providing bonuses to personnel to increase work motivation	(0.33, 0.192, 0.052)	0.191
	Holding training courses to increase individual abilities	(0.13, 0.092, 0.041)	0.088
	Creating welfare facilities for personnel	(0.012, 0.061, 0.033)	0.035

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4. Research findings

One of the most important stages of a simulation project is its validation. In fact, after choosing the appropriate tool for simulation, other important issues in model development, including verification and validation, should also be considered [9]. To confirm the hybrid simulation model of this research, logical tests were conducted with pre-designed scenarios and the hybrid simulation model was confirmed. In order to validate the hybrid simulation model, the data related to the production in the last 30 months of reality and the data of the simulation model during the same period were used and compared. In order to avoid correlation between the outputs of the simulation model, the simulation model was executed 30 times with different random seeds. Statistical processes have been carried out to confirm the validity of the model using Minitab software. The results are presented in the table below.

Table 3. Validation results of the hybrid simulation model

Title	Test type	Method used	P value
Data of 30 months of radiator product production (simulation model)	normality	Anderson-Darling	0.545
Data of 30 months of radiator product production (real world)	normality	Anderson-Darling	0.93
Data of 30 months of burner product production (simulation model)	normality	Anderson-Darling	0.418
Data of 30 months of burner product production (real world)	normality	Anderson-Darling	0.512
Data of 30 months of radiator product production (real world and simulation)	independence	Pearson	0.055
Data of 30 months of burner product production (real world and simulation)	independence	Pearson	0.983
Means equality test of reality and simulation model data of the burner product	Means equality	Paired t test	0.209
Means equality test of reality and simulation model data of the radiator product	Means equality	Paired t test	0.058

As is seen, due to the normality and independence of the data, the paired t-test was used. According to the p-value, the assumption of the equality of the average of the reality data and the data extracted from the simulation model for both burner and radiator products is confirmed, and the hybrid simulation model is validated. To extract and compare the simulation outputs of the current situation with the results of the optimization stage, the simulation model was run for 8760 hours (= 1year). The results are shown below.

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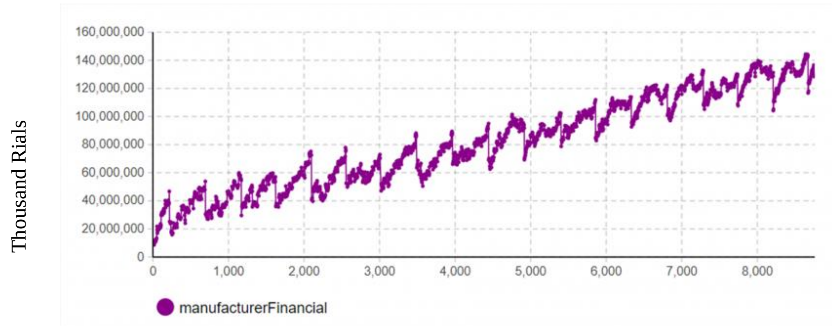

Figure 5. Manufacturer Liquidity (thousand Rials)

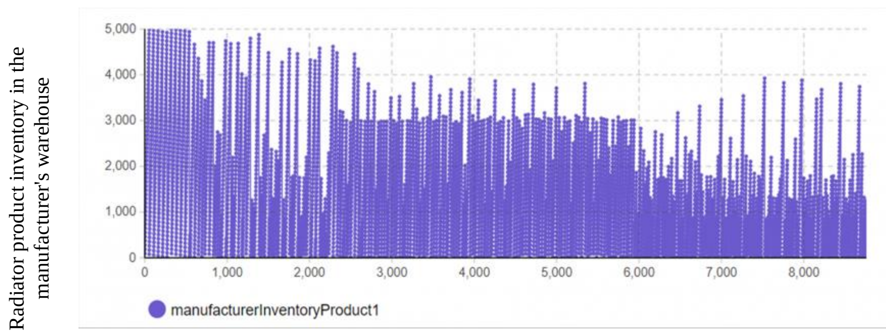

Figure 6. Radiator product inventory in the manufacturer's warehouse

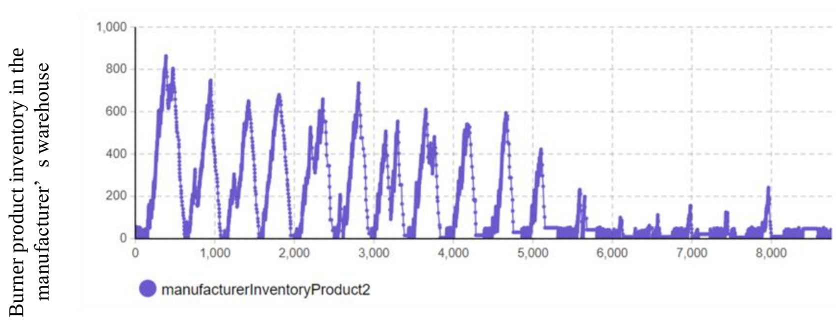

Figure 7. Burner product inventory in the manufacturer's warehouse

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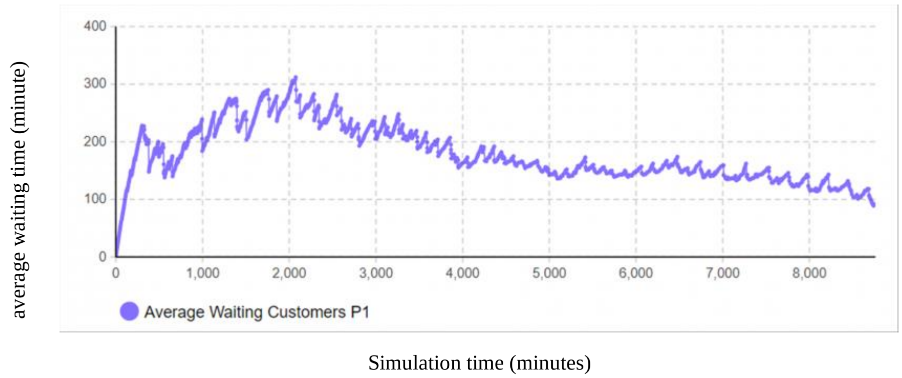

Figure 8. The average waiting time of customers to receive the radiator product

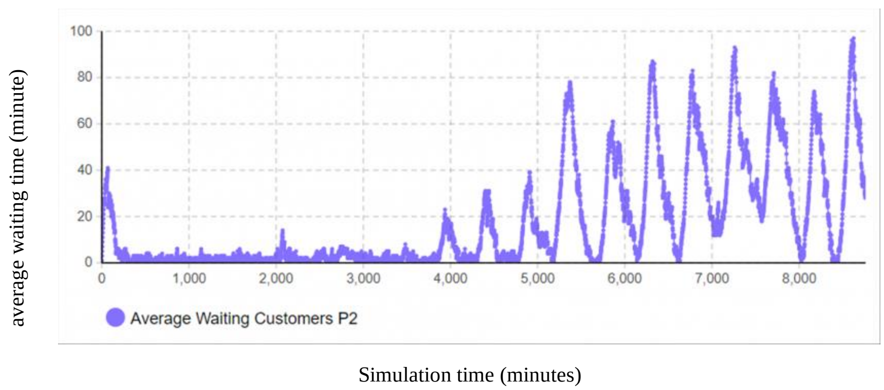

Figure 9. The average waiting time of customers to receive the burner product

From the graph related to the inventory of radiator and burner products in the manufacturer's warehouse, as well as the waiting time for customers of these two products, it is clear that the supply chain does not have the ability to meet customer demand without wasting time due to instability in the supply chain. Therefore, it is necessary to improve the performance of the chain by performing the optimization process.

At this stage, in order to increase the performance and sustainability of the supply chain and examine the performance of the chain from the economic, environmental and social perspectives, the optimization problem is defined with the goals of maximizing sustainability and minimizing costs. The decision variables of the optimization problem are described in Table 4.

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Table 4. Optimization problem variables

Row	Variable	Description
1	CW_i	The cost of waiting for the customer to receive the product i
2	W_i	The amount of waiting for customers to receive the product i
3	CH_i	The cost of maintaining product i in the chain
4	H_{ij}	The amount of storage of product i in the warehouse of agent j
5	CHM_k	The cost of keeping raw materials k in the warehouse of the manufacturer
6	M_k	The amount of storage of raw materials k in the warehouse of the manufacturer
7	$CSOS_a$	The cost of choosing the scenario of improvement of the social dimension a in the chain
8	$CENV_i$	The environmental costs of producing the i-th product, such as filter replacement and environmental pollution fines

The proposed optimization problem consists of the variables of ordering point decisions, maximum inventory level and method of improving the social dimension of the supply chain. Relevant descriptions are provided in Table 5.

Table 5. Decision variables of the optimization problem

Row	Decision variable	Description
1	LL_K	The lower limit of the order of raw materials k by the manufacturer
2	UL_K	The upper limit of the order of raw materials k by the manufacturer
3	$LL_{i.j}$	The lower limit of ordering product i by agent j
4	$UL_{i.j}$	The upper limit of the order of product i by agent j
5	P_a	Choosing social scenario a

By describing the variables of the optimization problem, the objective function is defined as follows.

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$$Min\ Z = \sum_i CW_i \times W_i + \sum_i \sum_j CH_{ij} \times H_{ij} + \sum_k CHM_k \times M_k + \sum_a CSOC_a \times P_a + \sum_i CENV_i \quad (1)$$

Constraints:

$$a \leq LL_K . UL_K . LL_{i.j} . UL_{i.j} \leq b \quad \forall k.i.j \quad (2)$$

$$LL_K < UL_K \quad \forall K \quad (3)$$

$$LL_{i.j} < UL_{i.j} \ \forall i.j \quad (4)$$

$$\sum_a P_a = 1 \quad (5)$$

The constraints of relation (2) are to determine the upper and lower limits for the decision variables and to specify the problem space for the meta-heuristic algorithm. Relations (3) and (4) guarantee that the maximum inventory levels of raw materials and products are greater than the minimum inventory level (order point). Relation (5) guarantees that one of the considered social scenarios is definitely selected.

To conduct the simulation optimization, OptQuest optimization package was used. The OptQuest optimization package, produced by OptTek, is one of the best simulation-optimization packages. This optimization package uses a combination of meta-heuristic algorithms such as Scatter Search, Tabu search, and genetic algorithm, in which the neural network is applied to determine the input parameters of algorithms [24].

The settings related to the optimization process by OptQuest are presented in Table 5.

Table 6. Optimization settings in OptQuest software

Specifications	Value
The number of iterations	15000
Duration of running the simulation model in each iteration	30240 hours
The number of iterations of convergence of the simulation model in each replication	Minimum: 30 iterations
	Max: 100 iterations
	Confidence level: 80 %

According to the stated goals of maximizing the sustainability of the supply chain and minimizing the costs, in the simulation model of the current situation, environmental aspects, including the replacement of filters to reduce emissions and the environmental fines, are added. Furthermore, the scenarios related to the social dimension and its impact on the increase in the production and the costs

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of each scenario are updated in the simulation model. The results of the simulation model of the current situation, taking into account the environmental and social dimensions, are presented below.

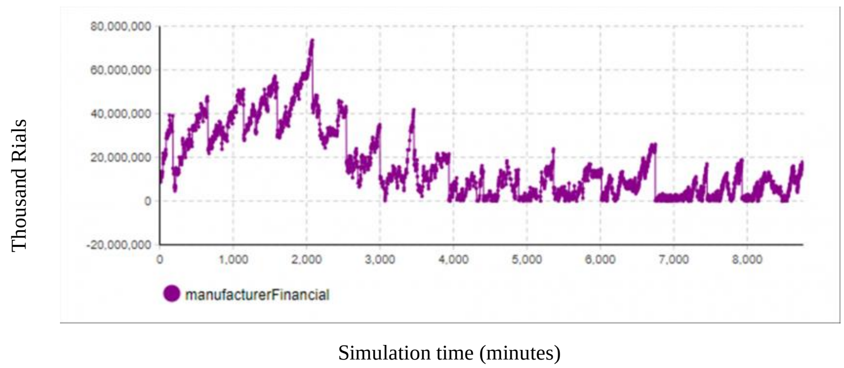

Figure 10. Manufacturer liquidity (thousand Rials) in current situation model with sustainability dimensions

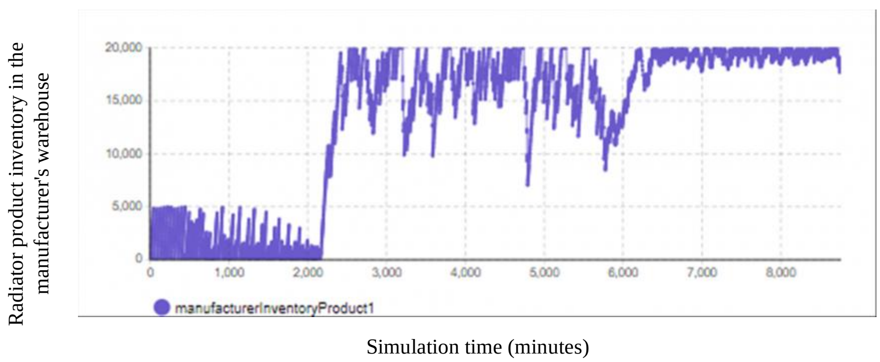

Figure 11. Radiator product inventory in the manufacturer's warehouse in the current situation model with sustainability dimensions

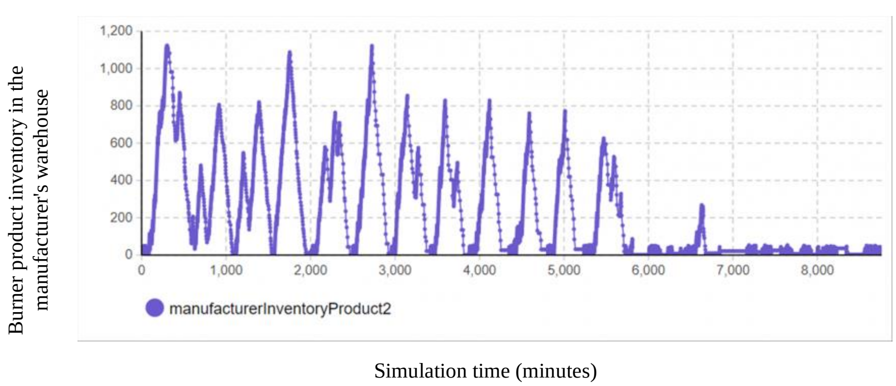

Figure 12. Burner product inventory in the manufacturer's warehouse in the current situation model with sustainability dimensions

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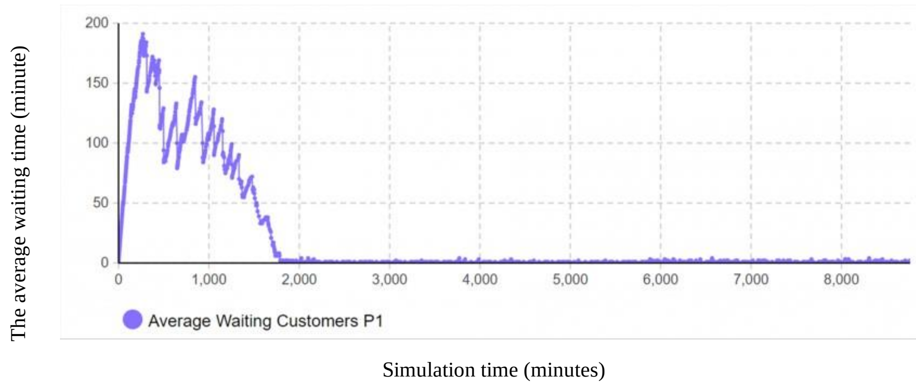

Figure 13. The average waiting time of customers to receive the radiator product in the current situation model with sustainability dimensions

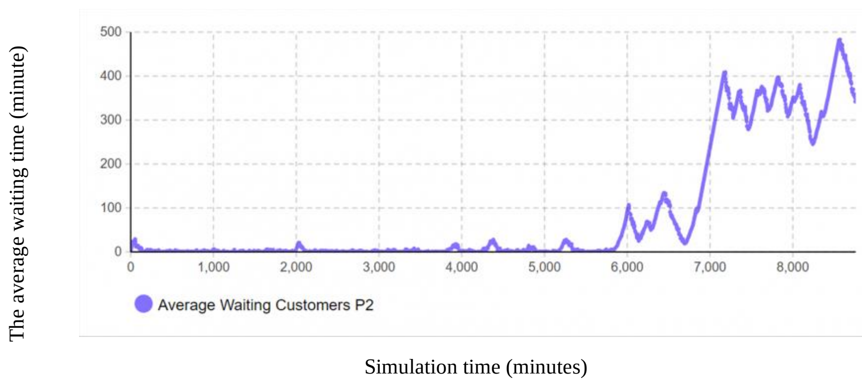

Figure 14. The average waiting time of customers to receive the burner product in the current situation model with sustainability dimensions

Considering the environmental and social aspects in the supply chain of the current situation, the supply chain loses its sustainability and the customers waiting time to receive the burner product increases. The financial status of the chain was also zero in many cases due to the spending on the environmental and social problems. To reduce the costs and increase the sustainability of the supply chain, the hybrid simulation-optimization process is implemented with the objective function of Relation (1) and its related constraints.

After performing the optimization process with the objective function and the defined constraints using hybrid simulation-optimization approach, the extracted optimal/near-optimal decision variables are entered into the simulation model, which include the minimum and maximum levels of inventory and the proposed scenarios for the social dimension of the supply chain. The sustainability assessment of the supply chain was performed through the outputs of the simulation model with optimized values, the results of which are presented below.

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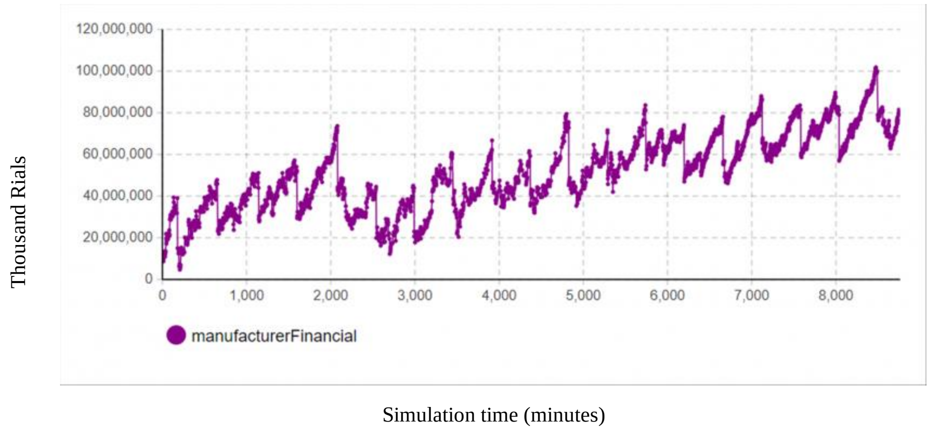

Figure 15. Liquidity of the manufacturer (thousand Rials) in the optimized sustainable supply chain

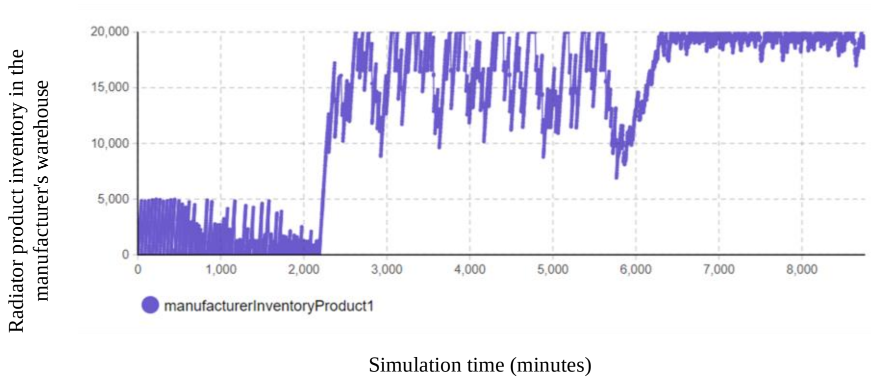

Figure 16. Radiator product inventory in the manufacturer's warehouse in the optimized sustainable supply chain

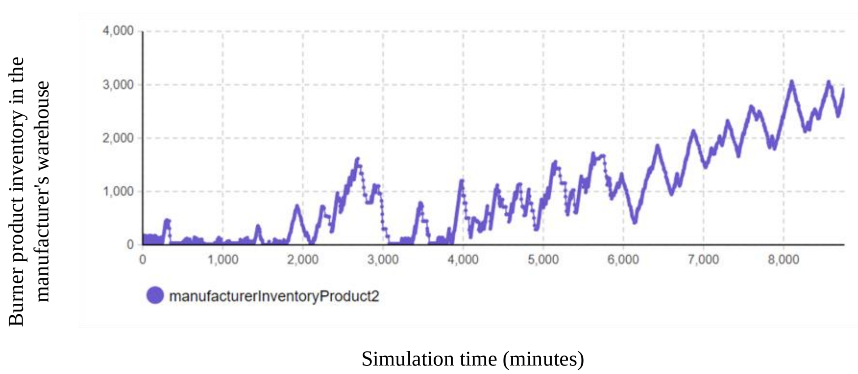

Figure 17. Burner product inventory in the manufacturer's warehouse in the optimized sustainable supply chain

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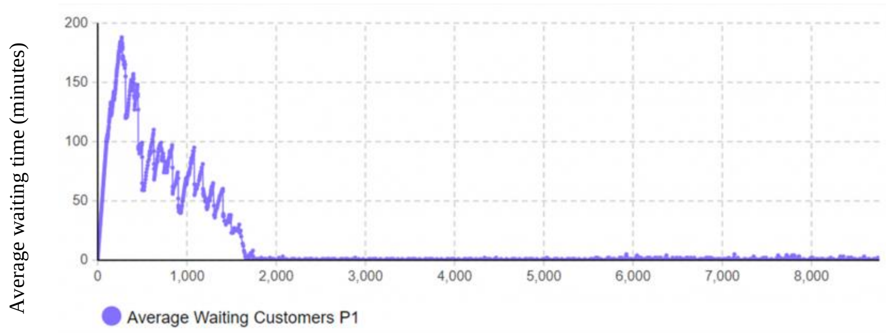

Figure 18. Average customer waiting time to receive the radiator product in the optimized sustainable supply chain

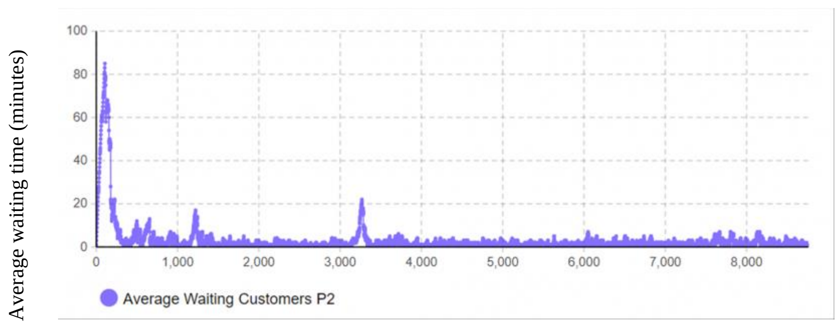

Figure 19. Average customer waiting time to receive the burner product in the optimized sustainable supply chain

According to the outputs of the optimized sustainable supply chain simulation model, the state of the chain has become completely sustainable after the optimization process. A significant improvement has also been achieved in the financial situation of the supply chain (Figure 15). The waiting time for customers to receive products has become almost zero (Figures 18 and 19). For the burner product, it has resulted in a reduction of 350 hours of customer waiting time. Besides, the inventory of radiator and burner products in the manufacturer's warehouse is in a favorable condition. It should be noted that the value of the objective function in the optimized model shows a 25% increase, compared to the current situation model with sustainability dimensions. This can be ascribed to the optimal / near optimal levels of inventory maintenance and ordering, the reduction of the maintenance costs, and the decrease in customers' waiting time to receive the said products.

5. Conclusion and suggestions

This research aimed to improve the supply chain sustainability using a hybrid simulation-optimization approach. For this purpose, economic, environmental and social objectives were simultaneously considered in the optimization problem. To the best of our knowledge, in previous studies, the use of the hybrid simulation-optimization approach to assess and increase the supply chain sustainability has been largely disregarded. Therefore, this study has tried to cover this research gap.

In designing the supply chain simulation model, a combination of agent-based modeling and discrete-event simulation was used. In the agent-based model, suppliers, manufacturers, distributors,

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retailers, and vehicles were included, and their behavior and interactions were formulated based on all the possibilities and uncertainties of the supply chain. Due to the need for modeling at the operational level of the production process in the manufacturer and the need to consider high details, the behavior of the manufacturer, production lines and related limitations were modeled by the discrete event simulation approach. To evaluate the performance of the designed hybrid model, it was implemented and studied in the supply chain of a company active in the ventilation industry.

As said before, the sustainability of the supply chain should be evaluated from the economic, environmental and social perspectives. For this purpose, the costs of maintaining raw materials and products and the costs caused by the lack of raw materials and products from an economic perspective, the implementation of various filters in production halls to reduce emissions and the related fines from an environmental perspective, and giving rewards to personnel to increase work motivation, holding training courses to increase individual abilities and creating welfare facilities for personnel from a social perspective were taken into account. Due to the complexity of how social dimensions affect supply chain performance, the fuzzy Delphi method was used to summarize experts' opinions.

The outputs of the simulation model of the current situation without considering the environmental and social dimensions showed that the performance of the supply chain does not show a stable situation. Accordingly, customers of radiator products wait for about 100 hours and customers of burner products wait for about 40 hours to receive the products. In the next step, environmental and social components were added to the current situation model. It was observed that despite the improvement in the way of fulfilling the burner demand, the chain's financial status is zero in many cases and the customers of the burner product are still waiting for about 350 hours to receive the product. In the next step, using meta-heuristic algorithms and optQuest optimization software, the hybrid simulation-optimization was carried out to minimize the costs of maintaining raw materials and products, costs of product shortages, social costs, and environmental costs. Optimal/near-optimal decision variables were updated in order to evaluate the current situation simulation model with sustainability dimensions. The improvements achieved by applying the simulation optimization approach and considering the dimensions of sustainability in the supply chain compared to the current situation are:

- Zero waiting time for customers to receive radiator and burner products
- An increase of 60 billion riyals in the liquidity of the manufacturer at the end of one year
- Improving the status of inventory maintenance for radiator and burner products in order to be able to respond to fluctuations
- 25% improvement in the objective function value.

It should be noted that at the end of one year, the inventory of burner and radiator products reached 20 thousand radiator blades and 3 thousand burners in the manufacturer's warehouse. Besides, the 25% improvement achieved in the value of the objective function was due to the reduction of shortages and maintenance costs.

The results showed that the implementation of environmental and social dimensions alone in the supply chain is not enough to create sustainability, and if the variables affecting the performance of the supply chain are not optimized, the sustainability of the chain may even deteriorate. Besides, the use of the hybrid simulation approach showed that all the details, probabilities and uncertainties in the supply chain can be easily modeled, with no need to adopt simplifying assumptions. The combination of meta-heuristic algorithms with the hybrid simulation model and the use of the simulation-optimization approach showed that this approach has the ability to effectively improve the sustainability of the supply chain.

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For future research, the following suggestions can be made:

Due to the appropriate performance of the hybrid simulation-optimization approach to evaluate the sustainability of the supply chain, it is suggested that this approach be used in other supply chains, especially supply chains with high complexity such as pharmaceutical products.

Considering the behavior and interactions of the customers, advertising, and performance of the manufacturer and its rivals, the current hybrid simulation model can give more accurate results regarding the customer behavior and effect on the sustainability of the supply chain.

The use of machine learning algorithms such as reinforcement learning is suggested to extract the optimal policy of inventory maintenance and ordering points and how to implement environmental and social aspects.

The use of the system dynamics modeling approach, along with the agent-based modeling and discrete-event simulation, makes it possible to examine macro-level and strategic components and their impact on supply chain sustainability.

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