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A Supply Chain Network Design by Considering Resiliency, Sustainability and Agility Approach in Home Appliances

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ABSTRACT

The Supply Chain Network Design (SCND) is crucial for enhancing the efficiency and effectiveness of operations in the home appliances industry. This study presents a mathematical model for designing a supply chain network that integrates sustainability, agility, and resiliency principles. These principles aim to optimize supply chain performance while considering environmental impact, responsiveness to changes, and the ability to recover from disruptions. The model incorporates multi-objective optimization techniques to balance economic, environmental, and social goals. A case study based on the home appliances industry is used to demonstrate the practical application of the model. Results indicate that the proposed model improves operational performance, reduces carbon emissions, and enhances the supply chain's resilience to disruptions.

1. Introduction

The global home appliances industry has become highly competitive, requiring manufacturers and distributors to focus not only on cost-efficiency and quality but also on sustainability, agility, and resiliency [1,2]. In this context, SCND plays a critical role in determining the performance of the entire system. Traditional SCND approaches have primarily focused on cost minimization, but the increasing emphasis on environmental sustainability, adaptability to market changes, and the need for resilience against disruptions have led to the development of more holistic models [3,4].

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This paper explores the integration of sustainability, agility, and resiliency in the design of a supply chain network for the home appliances industry. A mathematical model is developed to simultaneously address economic, environmental, and operational goals. The proposed model considers multiple objectives such as reducing carbon footprints, enhancing supply chain flexibility, and ensuring the system's robustness against potential disruptions.

The paper is organized as follows: the next section provides a review of the relevant literature on SCND with a focus on sustainability, agility, and resiliency. The methodology section presents the mathematical model and solution approach. Numerical results are then presented, followed by conclusions and recommendations for future research (see Figure 1).

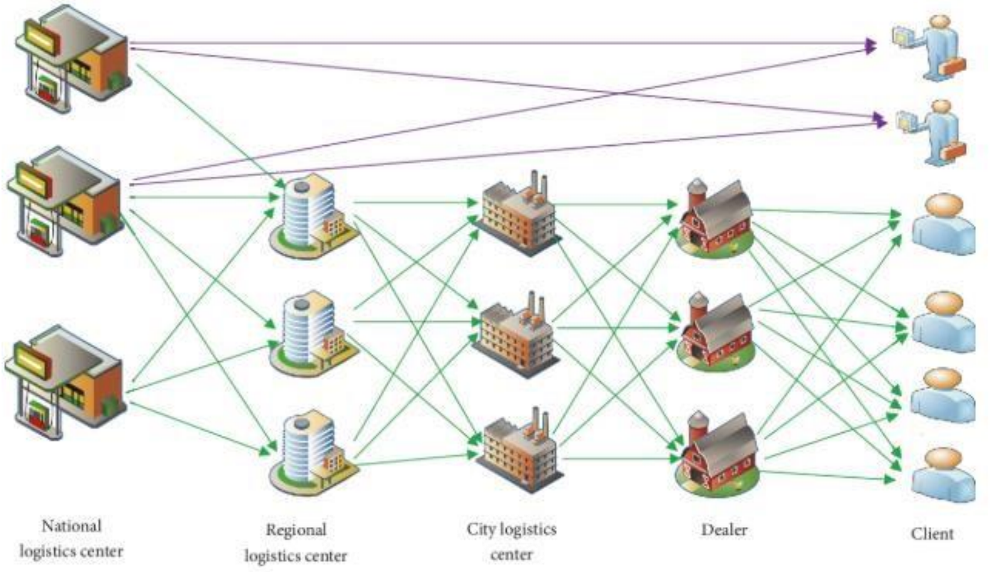


Figure 1: SCN Design (SCND).

This paper introduces a novel mathematical model for resilient SCND under uncertainty. The model takes into account multiple factors that contribute to supply chain resilience, such as demand fluctuations, disruptions, and the overall complexity of the supply chain. By considering these elements, the model aims to optimize network structure and decision-making processes to improve the supply chain's ability to withstand shocks and maintain operations during difficult situations.

The contributions of this paper to the existing literature include:

- Proposing a comprehensive Resilient, sustainable and agile SCND (RSASCND) framework that integrates resilience into SCND.

- Developing a Robust Stochastic Optimization (RSO) model to optimize network design while factoring in renewable energy integration.
- Demonstrating the effectiveness of the proposed model through an industry case study.

The remainder of the paper is organized as follows: The research is structured into five sections. Section 2 provides a literature review and discusses recent studies on SCND, highlighting gaps in the current research. Section 3 outlines the methodology used for calculations. Section 4 presents the results of the research. Finally, Section 5 offers insights and practical recommendations for managers, followed by the conclusion.

2. Survey related works

The literature on SCND is extensive and includes several key approaches, including cost minimization, optimization for environmental sustainability, and strategies for agility and resiliency. This section reviews the existing studies on each of these areas and highlights their relevance to home appliance supply chains.

2.1. Supply Chain Network Design (SCND) Overview

SCND involves determining the optimal configuration of the network, including facility locations, transportation routes, and inventory management. Early studies in SCND focused primarily on cost minimization and operational efficiency [1]. However, with the increasing importance of environmental concerns and market uncertainties, recent research has expanded the scope to include sustainability and risk management.

2.2. Sustainability in SCND

Sustainability in SCND refers to designing supply chains that minimize environmental impact while maintaining economic viability. Studies such as those by Seuring and Müller [2] have focused on incorporating environmental and social criteria into supply chain decisions. Methods like life cycle assessment (LCA) and carbon footprint analysis are commonly used to measure sustainability.

2.3. Agility in SCND

Agility refers to the ability of a supply chain to quickly adapt to changes in market demand, production schedules, and external disruptions. Studies like those of Yusuf et al. [3] highlight the importance of flexible supply chain structures that can rapidly respond to changes. Agility is particularly important in industries like home appliances, where market trends can change quickly.

2.4. Resiliency in SCND

Resilience in supply chains is the capacity to recover from disruptions, such as natural disasters, supplier failures, or economic shifts. Resilient supply chains can continue to deliver products under adverse conditions. Research on resilient supply chain design, such as that by Ponomarov and Holcomb [4], emphasizes the importance of redundancy, diversification, and flexibility in supply chain networks.

2.5. Mathematical Modeling in SCND

Mathematical models, especially those based on optimization techniques, have been widely used to address SCND problems. Mixed-integer linear programming (MILP), multi-objective optimization, and simulation-based models are commonly employed. Models integrating sustainability, agility, and resiliency are more recent, with studies like those by Tang and Tomlin [5] demonstrating how to balance these factors.

3. Problem Statement and Solution Approach

1. This section presents the mathematical model developed to design a supply chain network that incorporates sustainability, agility, and resiliency. The model is based on multi-objective optimization, where the following objectives are considered:
2. **Cost minimization**: Includes transportation, production, and inventory holding costs [6].
3. **Environmental impact minimization**: Includes carbon emissions from transportation and manufacturing processes [7].
4. **Agility maximization**: Evaluate the flexibility of the network to adapt to changes in demand and supply conditions [8].
5. **Resiliency maximization**: Measures the ability of the network to recover from disruptions, such as factory shutdowns or transportation delays [9].

3.1. Model Structure

- The home appliances supply chain consists of multiple suppliers, manufacturing plants, and distribution centers.
- Demand is stochastic and can change over time, reflecting market conditions.
- Disruptions can occur, affecting transportation or production capacity.
- Sustainability factors are quantified in terms of carbon emissions [10-11].

3.2. Mathematical Formulation

The RSO model is a mathematical programming approach designed to optimize the configuration of the RSASCND network (see Figure 2). It takes into account various factors, including:

Based on the problem definition, the following assumptions are made:

Assumptions:

- Partial demand must be addressed, and shortages are not allowed.
- Flow and capacity constraints are integrated with a resilience strategy.
- The resilience strategy includes flexible capacity and redundancy within facilities or across multiple resources.

The use of the RSO model is beneficial for enhancing resilience in the face of demand fluctuations:

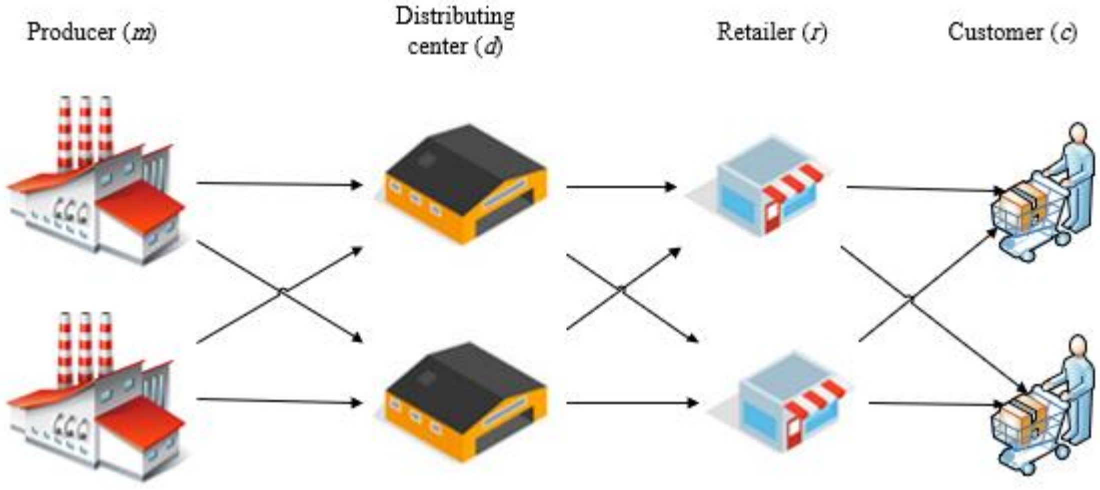


Figure 2: RSASCND.

Sets, parameters, and variables definition:

Sets (Indices):

m	Set of producers (manufacturers), $m \in M = \{1,2,...,\bar{m}\}$,
d	Set of distributors, $d \in D = \{1,2,...,\bar{d}\}$,
r	Set of retailers, $r \in R = \{1,2,...,\bar{r}\}$,
c	Set of customers, $c \in C = \{1,2,...,\bar{c}\}$,
p	Set of products (commodity), $p \in P = \{1,2,...,\bar{p}\}$,
t	Set of time period, $t \in T = \{1,2,...,\bar{t}\}$,
s	Set of scenarios, $s \in S = \{1,2,...,s\}$.

Parameters	Description	Amount of parameter	Unit
de_{cpts}	Demand for product p in customer c in time t based on scenario s,	U(3000,4000)	Number
Costs:			
fcm_m	Set up cost for producer m,	U(1,1.2)*1000000	Dollar
fcd_d	Set up cost for distributor d,	U(0.5,0.6)*1000000	Dollar
fcr_r	Set up cost for retailer r,	U(0.3,0.4)*1000000	Dollar
vmd_{mdpts}	Variable cost for transportation from producer m to disturbuter d for product p in time t based on scenario s,	U(4,4.2)/1000	Dollar
vdr_{drpts}	Variable cost for transportation from disturbuter d to retailer r for product p in time t based on scenario s,	U(3.9,4)/1000	Dollar
vrc_{rcpts}	Variable cost for transportation from retailer r to customer c for product p in time t based on scenario s,	U(3,4)/1000	Dollar
CO2 emission:			
emm_m	Set up emission for producer m,	200*U(7,8)	Ton
emd_d	Set up emission for distributor d,	50*U(7,8)	Ton
emr_r	Set up emission for retailer r,	20*U(7,8)	Ton
$emmd_{mdpts}$	Variable emission for transportation from producer m to disturbuter d for product p in time t based on scenario s,	U(4,4.2)/1000	Ton
$emdr_{drpts}$	Variable emission for transportation from disturbuter d to retailer r for product p in time t based on scenario s,	U(3.9,4)/1000	Ton
$emrc_{rcpts}$	Variable emission for transportation from retailer r to customer c for product p in time t based on scenario s,	U(3,4)/1000	Ton
$MaxEm$	Maximum emission.	4400	Ton

Capacity:

Cpm_{mpts}	Capacity of producer m for product p in time t based on scenario s,	U(40500,41000)	Number
Cpd_{dpts}	Capacity of disturbuter d for product p in time t based on scenario s,	U(38500,39000)	Number
Cpr_{rpts}	Capacity of retailer r for product p in time t based on scenario s,	U(45000,46000)	Number

Other parameters

p_s	Scenario probability s,	s/(|S|(|S|+1))/2	Percent
prm_m	Access level of producer m,	U(95,98)	Percent
prd_d	Access level of distributor d,	U(95,98)	Percent
prr_r	Access level of retailer r,	U(95,98)	Percent
Ω	Resiliency coefficient,	60	Percent
δ	Agility coefficient,	100	Percent

Decision variables:

Binary (zero-one) variables:

lm_m	Equal one, if producer m is set up; else zero,
ld_d	Equal one, if distributor d fis set up; else zero,
lr_r	Equal one, if retailer r is set up; else zero,

Positive (Continues) variables:

ymd_{mdpts}	Flow quantity from producer m to disturbuter d for product p in time t based on scenario s,
ydr_{drpts}	Flow quantity from disturbuter d to retailer r for product p in time t based on scenario s,
yrc_{rcpts}	Flow quantity from retailer r to customer c for product p in time t based on scenario s,

Auxiliary (slack) variables:

Z	Objective function,
FC	Total fixed cost,
VC_s	Total variable cost for scenario s,
Γ_s	Total fixed and variable cost for scenario s,

FEm	Total fixed emission,
VEm_s	Total variable emission for scenario s,
Γ'_s	Total fixed and variable emission for scenario s,

Model 1: RSASCND.

$$\text{minimize}\, Z = \sum_s p_s \Gamma_s, \tag{1}$$

subject to:

Cost constraints:

$$\Gamma_s = FC + VC_s, \tag{2}$$

$$FC = \sum_m fm_m lm_m + \sum_d fd_d ld_d + \sum_r fr_r lr_r, \tag{3}$$

$$\begin{aligned} VC_s = \sum_p \sum_t (\sum_m \sum_d vmd_{mdpts} ymd_{mdpts} \\ + \sum_d \sum_r vdr_{drpts} ydr_{drpts} + \sum_r \sum_c vrc_{rcpts} yrc_{rcpts}), \end{aligned} \quad \forall s \tag{4}$$

Balance requirements and Agility strategy (Forward flow):

$$\sum_r yrc_{rcpts} \geq \delta de_{cpts}, \quad \forall c, p, t, s \tag{5}$$

$$\sum_d ydr_{drpts} \geq \sum_c yrc_{rcpts}, \quad \forall r, p, t, s \tag{6}$$

$$\sum_m ymd_{mdpts} \geq \sum_r ydr_{drpts}, \quad \forall d, p, t, s \tag{7}$$

Resiliency strategy (flexible capacity):

$$\sum_c yrc_{rcpts} \leq prr_r Cpr_{rpts} lr_r, \quad \forall r, p, t, s \tag{8}$$

$$\sum_r ydr_{drpts} \leq prd_d Cpd_{dpts} ld_d, \quad \forall d, p, t, s \tag{9}$$

$$\sum_d ymd_{mdpts} \leq prm_m Cpm_{mpts} lm_m, \quad \forall m, p, t, s \tag{10}$$

$$\min\{\frac{\sum_m lm_m}{|M|}, \frac{\sum_d ld_d}{|D|}, \frac{\sum_r lr_r}{|R|}\} \geq \Omega, \tag{11}$$

Sustainability strategy:

$$FEm = \sum_m em_m lm_m + \sum_d ed_d ld_d + \sum_r er_r lr_r, \tag{12}$$

$$VEm_s = \sum_p \sum_t (\sum_m \sum_d emmd_{mdpts} ymd_{mdpts} + \sum_d \sum_r emdr_{drpts} ydr_{drpts} + \sum_r \sum_c emrc_{rcpts} yrc_{rcpts}), \quad \forall s \qquad (13)$$

$$\Gamma'_s = FEm + VEm_s, \quad \forall s \qquad (14)$$

$$\Gamma'_s \leq MaxEm, \qquad (15)$$

Decision variables:

$$lm_m, ld_d, lr_r \in \{0,1\}, \quad \forall m, d, r \qquad (16)$$

$$ymd_{mdpts}, ydr_{drpts}, yrc_{rcpts} \geq 0, \quad \forall m, d, r, c, p, t, s \qquad (17)$$

The objective function (1) minimizes the cost function for all scenarios. Constraint (2) presents fixed and variable costs for the facility and each scenario. Constraint (3) shows the fixed cost for the facility. Constraints (4) show variable costs for setting up facilities for each scenario. Constraints (5) - (7) present forward flow quantity constraints, including demand satisfaction and balance between forward flow facilities. Constraints (8) to (10) state capacity constraint with a flexible approach as a resiliency strategy dependent on the scenario. Constraints (11) explain redundancy and multi-source constraint as a second resiliency strategy greater than the resiliency coefficient. Constraints (12) to (15) state sustainability strategy as a maximum strategy. Constraints (16) define activation binary variables for locations and the pillar of SCND that is set up if equal to one. Constraints (17) define the flow quantity variables that are positive or non-negative variables between the forward and reverse of CLSC.

The objective function of the RSO model aims to minimize the expected total cost of the SCN across all demand scenarios. This includes production and transportation costs. The model also incorporates constraints related to capacity limitations, demand satisfaction, and material flow balance.

3.3. Solution Approach

The RSO model is a complex mixed-integer linear program (MILP) that can be solved using specialized optimization software. The solution process involves:

1. Formulating the mathematical model with sets, parameters, and decision variables.
2. Defining the objective function and constraints.

3. Specifying the demand scenarios and their associated probabilities.

4. Utilizing optimization software to solve the model and obtain the optimal network design (see Figure 3) [10-12].

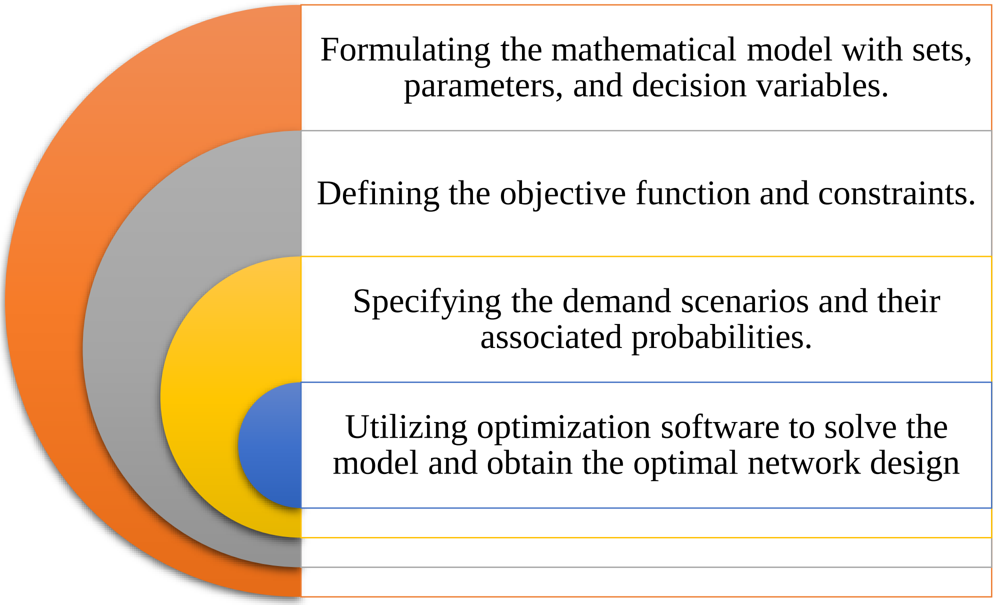


Figure 3: Solution approach.

4. Results and discussion

This section presents a case study to showcase the effectiveness of the proposed RSASCND framework and RSO model. The case study examines an automated parts supply chain with a network comprising potential manufacturing facilities, distributors, retailers, and customer markets. Data related to demand, production costs, transportation expenses, and facility capacities are gathered for each network component. Furthermore, historical data or expert judgment is used to estimate disruption probabilities for various scenarios, such as natural disasters and economic downturns.

Multiple demand scenarios are generated to simulate potential disruptions, including demand fluctuations in specific customer markets or disturbances at certain facilities. The probability of each scenario occurring is also defined. The RSO model is implemented using mathematical programming software like CPLEX, with the gathered data and defined scenarios populating the model parameters. The model is then solved to determine the optimal RSASCND network design.

The solution provided by the RSO model offers insights into the best configuration of the supply chain network (SCN). While the specific results depend on the input data and selected scenarios, the case study highlights how the RSASCND framework and RSO model are effective in designing a resilient SCN that minimizes environmental impact (see Tables 1, 2 and Figures 4 and 5).

Table 1. A number of indices and the cost function of the case study.

Problem	$\lvert M\rvert\lvert D\rvert\lvert R\rvert\lvert C\rvert\lvert P\rvert\lvert T\rvert\lvert S\rvert$	**Cost (Dollar)**	**Max CO₂ emission**	**Time (second)**
Main model	3.3.3.3.3.3.3	3796521.607	4400	0.264

Table 2. Final locations for RSASCND.

Variables	**City**		
Manufacturer (xm_m)	Tehran	Oroumieh	Mashhad
	1	0	1
Distributor (xd_d)	Tehran	Mashhad	Sanandaj
	1	1	0
Retailer (xr_r)	Mashhad	Tehran	Sanandaj
	1	1	0

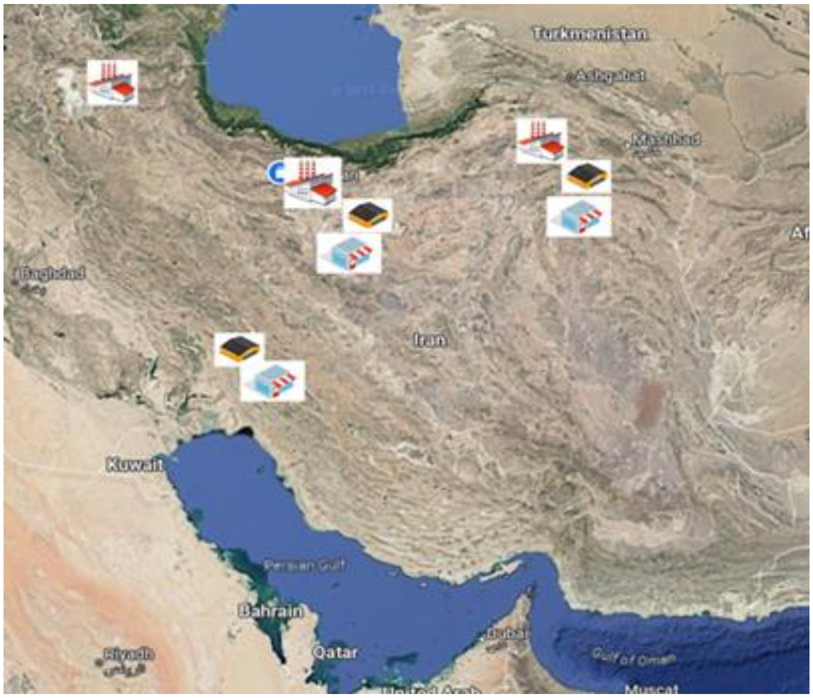


Figure 4: Facility components.

Figure 5: Results of RSASCND.

4.1. Analysis of resiliency coefficient

In this section, the resiliency coefficient (Ω) is changed between 10% to 60%. As can be seen, varying the resiliency coefficient increases cost function (see Table 3, Figure 6, and Figure 7). It is considered that when the resiliency coefficient increases, the mathematical model wants to increase responsibility. As a result, the cost function increases.

Table 3. Analysis of resiliency coefficient on cost function.

Problem	Resiliency coefficient (Ω)	Cost (Dollar)	Time (second)
Main model	10%	1857231.947	0.214
	20%	1857231.947	0.189
	30%	1857231.947	0.189
	40%	3796521.607	0.191
	60%	3796521.607	0.191

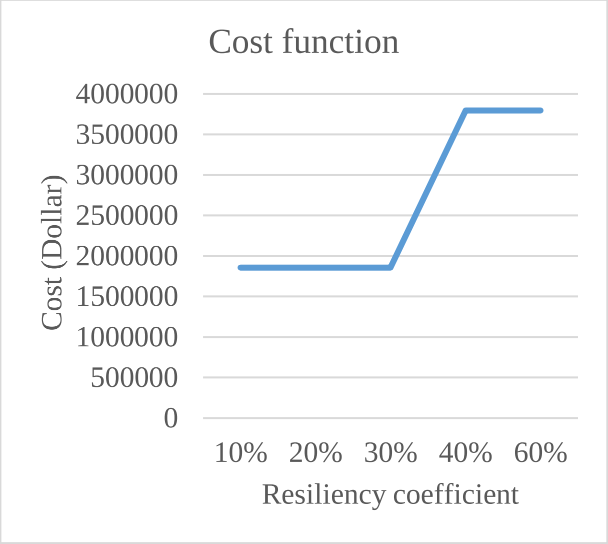


Figure 6: Analysis of resiliency coefficient on the cost function.

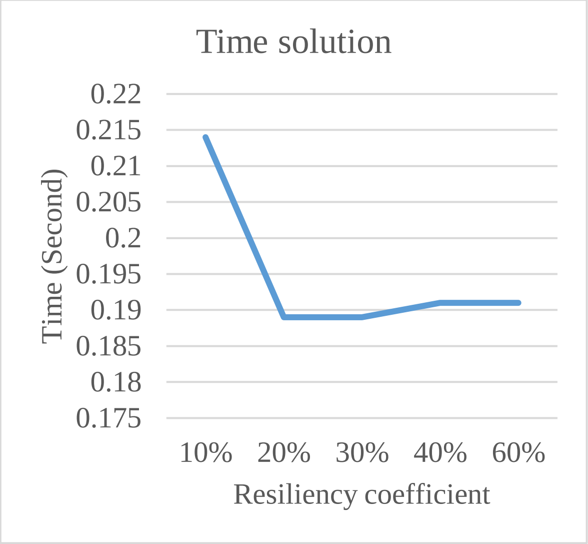


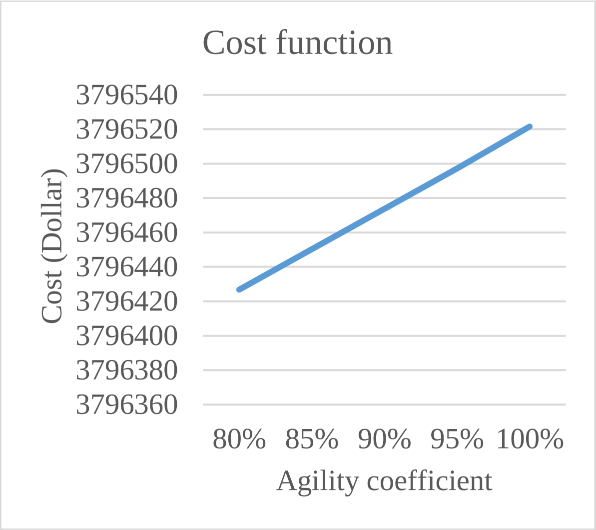
Figure 7: Analysis of resiliency coefficient on time solution.

4.2. Analysis of agility coefficient

In this section, the agility coefficient (δ) is changed between 10% to 60%. As can be seen, varying the resiliency coefficient increases cost function (see Table 4, Figure 8, and Figure 9). It is considered that when the agility coefficient decreases, the mathematical model wants to decrease responsibility. As a result, the cost function decreases.

Table 4. Analysis of agility coefficient on cost function.

Problem	Agility coefficient (δ)	Cost (Dollar)	Time (second)
Main model	80%	3796426.79	0.244
	85%	3796450.27	0.23
	90%	3796473.76	0.255
	95%	3796497.25	0.258
	100%	3796521.61	0.191



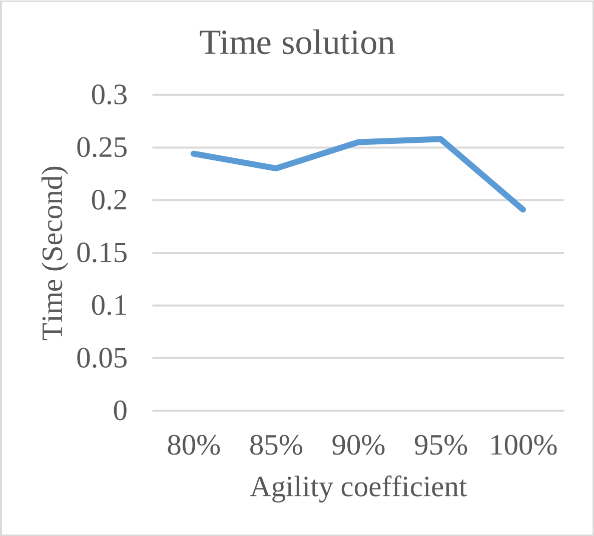


Figure 8: Analysis of agility coefficient on the cost function.

Figure 9: Analysis of agility coefficient on time solution.

5. Conclusion

This study presents a mathematical model for SCND that integrates sustainability, agility, and resiliency for the home appliances industry. The model provides a framework for optimizing the supply chain while considering environmental impacts, flexibility, and risk management. The results from the case study demonstrate that the proposed approach can significantly improve supply chain performance across multiple dimensions. Future research can focus on refining the model to include more realistic disruptions, considering supply chain collaboration, and incorporating real-time data.

This research has presented a comprehensive approach to designing sustainable, agile, and resilient supply chain networks for the home appliance industry. By integrating these three critical dimensions into a mathematical model, we have demonstrated the potential to optimize network configurations while mitigating risks, reducing environmental impact, and enhancing responsiveness to market fluctuations.

The numerical results have highlighted the significant impact of considering sustainability, agility, and resilience on the network design. The proposed model has been shown to effectively balance these competing objectives, leading to more robust and efficient supply chain networks. Sensitivity analysis has further revealed the critical factors that influence the network design and the trade-offs involved.

While this research has made significant strides in advancing supply chain network design, several avenues for future research remain. Firstly, incorporating uncertainty and dynamic factors, such as demand fluctuations and supply disruptions, into the model can enhance its practical applicability. Secondly, exploring the integration of emerging technologies, such as blockchain and artificial intelligence, can further improve the resilience and efficiency of supply chain networks. Additionally, investigating the social and ethical implications of sustainable and resilient supply chain practices is crucial for long-term impact.

By addressing these research directions, we can contribute to the development of more sustainable, agile, and resilient supply chain networks that can meet the evolving needs of the home appliance industry and society as a whole.

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