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Resilience, and Agile Closed-Loop Supply Chain Network Design by Considering Renewable Energy

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ABSTRACT

This paper explores the integration of resilience, agility, and closed-loop practices within supply chain network design (SCND) while incorporating renewable energy sources. A novel Resilience, and Agile Closed-Loop Supply Chain Network (RACLSCND) concept is introduced, aiming to achieve sustainability and robustness in a circular economy. The literature review examines existing research on resilient SCND, closed-loop supply chains, and the role of renewable energy in these systems. The methodology proposes a Robust Stochastic Optimization (RSO) model that considers factors like renewable energy integration, facility location, capacity planning, and material flow optimization. Numerical results demonstrate the effectiveness of the model in a case study from the home appliance industry. The model optimizes network design while minimizing carbon footprint and ensuring adaptability to demand fluctuations. The conclusion emphasizes the significance of RACLSCND as a future-proof approach for sustainable and resilient supply chain management.

1. Introduction

The globalized nature of modern supply chains exposes them to various disruptions, including natural disasters, political instability, and economic fluctuations. These disruptions can significantly impact production, delivery, and ultimately, customer satisfaction. Building resilience in supply chain networks has become a critical priority for businesses seeking long-term success. Furthermore, the growing focus on sustainability necessitates the adoption of closed-loop practices that minimize waste and maximize resource recovery. This paper presents a novel

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approach that integrates resilience, agility, and closed-loop principles within supply chain network design while considering renewable energy sources.

The proposed approach RACLSCND aims to achieve a balance between environmental, economic, and social objectives. By incorporating renewable energy sources like solar or wind power, RACLSCND seeks to reduce dependence on fossil fuels and minimize the carbon footprint of the supply chain. Additionally, the framework emphasizes agility to adapt to changing market demands and disruptions (see Figure 1) [1].

Figure 1: RACLSCND Design by Considering Renewable Energy.

This paper contributes to the existing body of knowledge by:

- Proposing a comprehensive RACLSCND framework that integrates resilience, agility, and closed-loop practices in SCND.
- Developing a Robust Stochastic Optimization (RSO) model to optimize network design while considering renewable energy integration.
- Demonstrating the effectiveness of the proposed model through a case study in the home appliance industry

This research is arranged into five sections. Section 2 defines the literature review and recent studies in the area of CLSCND and tries to show the gap in research. Section 3 suggests a methodology for calculation. Section 4 proposes the results of this research. Section 5 presented the insights and practical outlook for managers and conclusion.

2. Survey related works

Resilient Supply Chain Network Design (SCND):

Extensive research has been conducted on building resilience in SCNs. Many studies emphasize strategies like diversification of suppliers, redundancy in production facilities, and flexible transportation options to mitigate the impact of disruptions [1, 2]. For example, Jüttner et al. [1] propose a risk management framework for SCND that incorporates risk identification, assessment, and mitigation strategies. Similarly, Sheffi and Rice [2] discuss the importance of building flexibility into supply chains to adapt to changing market conditions.

Closed-Loop Supply Chains (CLSC):

Closed-loop supply chains focus on recovering and reusing materials from end-of-life products. This approach reduces waste generation and promotes resource conservation. A growing body of research explores different aspects of CLSCs, including design, reverse logistics, and economic viability [3, 4]. For instance, Guide et al. [3] present a framework for designing closed-loop supply chains for product recovery and reuse. Additionally, De Souza et al. [4] analyze the economic and environmental benefits of closed-loop supply chains in various industries.

Renewable Energy in Supply Chains:

The integration of renewable energy sources like solar, wind, and geothermal power is gaining traction in supply chain management. This approach helps reduce dependence on fossil fuels and minimizes greenhouse gas emissions [5, 6]. For example, Fahim et al. [5] investigate the economic and environmental implications of integrating renewable energy into production processes within supply chains. Similarly, Hosseini et al. [6] explore the use of renewable energy for powering transportation fleets in supply chains.

Gap and Research Contribution:

While existing research addresses resilience, closed-loop practices, and renewable energy in supply chains individually, a limited body of work integrates these concepts into a comprehensive framework. This paper addresses this gap by proposing the RACLSCND framework and developing a corresponding RSO model. The model optimizes network design while considering factors like renewable energy integration, facility location, capacity planning, and material flow optimization under demand uncertainty.

3. Problem Statement and Solution Approach

This section outlines the methodology for designing a resilient, agile, and CLSCND with renewable energy integration.

RACLSCND Framework:

The RACLSCND framework consists of four key pillars:

1. **Resilience:** This pillar emphasizes strategies to mitigate the impact of disruptions on the supply chain. Redundancy in facilities, diversification of suppliers, and flexible capacity planning are essential aspects of building resilience [7-10].

2. **Agility:** This pillar focuses on the ability of the supply chain to adapt to changing market demands and disruptions. Real-time data analytics, flexible production processes, and collaborative partnerships with suppliers and customers are crucial for agility [10-15].

3. **Closed-Loop Practices:** This pillar emphasizes the recovery and reuse of materials from end-of-life products. Reverse logistics networks, disassembly facilities, and remanufacturing capabilities are key elements of closed-loop supply chains [15-18].

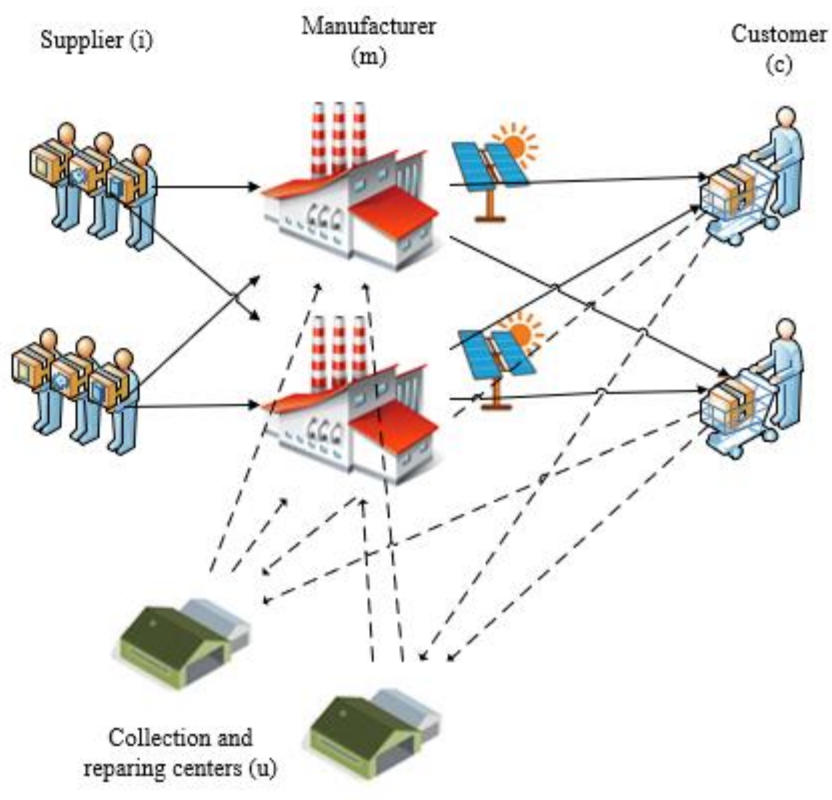

Figure 2: RACLSCND Design by Considering Renewable Energy.

3.1. Mathematical model

Robust Stochastic Optimization (RSO) Model:

The RSO model is a mathematical programming approach that optimizes the design of the RACLSCND network. The model considers various factors, including:

Based on the problem statement, these assumptions are assumed as follows:

Assumptions:

- Partial demand should be responded to, and the shortage is permitted (agility),
- RE can establish if the model needs,

- Flow and capacity limitations with the resiliency approach are activated (resiliency, agility),
- A resilience strategy includes flexible capacity and redundancy in facility or multi-resource are set up (resiliency),
- Utilizing RSO is helpful for resilience and risk-aversion to face demand variation.

Sets, parameters and variables definition:

Sets (Indices):

i	Set of suppliers (vendors) $i \in I = \{1,2,...,\bar{i}\}$,
m	Set of producers (manufacturers), $m \in M = \{1,2,...,\bar{m}\}$,
c	Set of customers, $c \in C = \{1,2,...,\bar{c}\}$,
u	Set of collection centers, $u \in U = \{1,2,...,\bar{u}\}$,
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(3,4)*1000*((s-1)*0.5+1)	Number
Costs:			
fi_i	Set up cost for supplier i,	U(1,2)*1000	Dollar
fm_m	Set up cost for producer m,	U(4,5)*10000	Dollar
fu_u	Set up cost for collection centers u,	U(2,3)*1000	Dollar
fre	Set up cost for RE for CLSCND,	|M|*10*33333/1000	Dollar
vim_{impts}	Variable cost for transportation from vendor i to producer m for product p in time t based on scenario s,	U(3,4)/1000*((s-1)*0.5+1)	Dollar

vmc_{mcpts}	Variable cost for transportation from producer m to customer c for product p in time t based on scenario s,	U(3,4)/1000*((s-1)*0.5+1)	Dollar
vcu_{cupts}	Variable cost for transportation from customer c to collection centers u for product p in time t based on scenario s,	U(3,4)/1000*((s-1)*0.5+1)	Dollar
vum_{umpts}	Variable cost for transportation from collection centers u to producer m for product p in time t based on scenario s,	U(3,4)/1000*((s-1)*0.5+1)	Dollar
Capacity:			
Cpi_{ipts}	Capacity of vendor i for product p in time t based on scenario s,	U(3,4)*10000*((s-1)*0.5+1)	Dollar
Cpm_{mpts}	Capacity of producer m for product p in time t based on scenario s,	U(3,4)*10000*((s-1)*0.5+1)	Dollar
Cpu_{upts}	Capacity of collection centers u for product p in time t based on scenario s,	U(3,4)*10000*((s-1)*0.5+1)	Dollar
Other parameters			
p_s	Scenario probability s,	1/|S|	Percent
ρ	Recovery rate from customers to collection centers,	U(0,10)	Percent
ρ'	Remanufacturing rate to manufacturing from collection centers,	30	Percent
pri_i	Access level of supplier i,	U(95,98)	Percent
prm_m	Access level of producer m,	U(95,98)	Percent
pru_u	Access level of collection centers u,	U(95,98)	Percent
Ω	Resiliency coefficient,	60	Percent
δ	Agile coefficient.	80	Percent

Decision variables:

Binary (zero-one) variables:

xi_i	Equal one, if vendor i is set up; else zero,
xm_m	Equal one, if producer m is set up; else zero,
xu_u	Equal one, if collection center u is set up; else zero,
xre	Equal one, if renewable energy is set up; else zero,

Positive (Continues) variables:

yim_{impts}	Flow quantity from supplier i to producer m for product p in time t based on scenario s,
ymc_{mcpts}	Flow quantity from producer m to customer c for product p in time t based on scenario s,
ycu_{cupts}	Flow quantity from customer c to collection centers u for product p in time t based on scenario s,
yum_{kmpts}	Reverse quantity from collection centers u to producer m for product p in time t based on scenario s,

Auxiliary (slack) variables:

FC	Total fixed cost,
$FC1$	Total fixed cost of setting up facilities,
$FC2$	Total fixed cost of setting up renewable energy,
VC_s	Total variable cost for scenario s,
Γ_s	Total fixed and variable cost for scenario s,

Model 1: Robust and risk-averse NZRACLSCND with considering renewable energy.

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

subject to:

Cost constraints:

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

$$FC = FC1 + FC2, \tag{3}$$

$$FC1 = \sum_i fi_i xi_i + \sum_m fm_m xm_m + \sum_u fu_u lu_u, \tag{4}$$

$$FC2 = fre.xhr, \tag{5}$$

$$VC_s = \sum_p \sum_t (\sum_i \sum_m vim_{impts} yim_{impts} + \sum_m \sum_c vmc_{mcpts} ymc_{mcpts} + \sum_c \sum_u vcu_{cupts} ycu_{cupts} + \sum_u \sum_m vum_{umpts} yum_{umpts}), \quad \forall s \quad (6)$$

Balance and agile requirements (Forward flow):

$$\sum_m ymc_{mcpts} \geq \delta de_{cpts}, \quad \forall c,p,t,s \quad (7)$$

$$\sum_i yim_{impts} + \sum_u yum_{umpts} = \sum_c ymc_{mcpts}, \quad \forall m,p,t,s \quad (8)$$

Balance requirements (Reverse flow):

$$\sum_u ycu_{cupts} \geq \rho de_{cpts}, \quad \forall c,p,t,s \quad (9)$$

$$\sum_u yum_{umpts} \leq \rho' \sum_c ycu_{cupts}, \quad \forall u,p,t,s \quad (10)$$

Resiliency strategy (flexible capacity):

$$\sum_c ymc_{mcpts} \leq prm_m Cpm_{mpts} xm_m, \quad \forall m,p,t,s \quad (11)$$

$$\sum_m yim_{impts} \leq pri_i Cpi_{ipts} xi_i, \quad \forall m,p,t,s \quad (12)$$

$$\sum_c ycu_{cupts} \leq pru_u Cpu_{upts} xu_u, \quad \forall u,p,t,s \quad (13)$$

Resiliency strategy (redundancy and multi-source):

$$\frac{\sum_i xi_i}{|I|} \geq \Omega, \quad (14)$$

$$\frac{\sum_m lm_m}{|M|} \geq \Omega, \quad (15)$$

$$\frac{\sum_u lu_u}{|U|} \geq \Omega, \quad (16)$$

Decision variables:

$$xi_i, xm_m, xu_u \in \{0,1\}, \quad \forall i,m,u \quad (17)$$

$$yim_{impts}, ymc_{mcpts}, ycu_{cupts}, yum_{umpts} \geq 0, \quad \forall i,m,c,u,p,t,s \quad (18)$$

The objective function (1) aims to minimize cost function for all scenario. Constraint (2) - (5) show fixed for facility and renewable energy. Constraints (6) show variable costs for setting up facilities for each scenario. Constraints (7) - (8) present forward flow quantity constraints, including demand satisfaction as agile requirements and balance between forward flow facilities. Constraints (9) – (10) present reverse flow quantity constraints, including waste flow and balance between reverse flow facilities. Constraints (11) to (13) state capacity constraint with a flexible approach as a resiliency strategy dependent on the scenario. Constraints (14)-(16) explain redundancy and multi-source constraint as a second resiliency strategy greater than the resiliency coefficient. Constraints (17) define activation binary variables for locations and solar renewable energy, and the pillar of CLSC is set up if equal to one. Constraint (18) defines the flow of 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 supply chain network across all demand scenarios. This includes production costs, transportation costs, collection costs, remanufacturing costs, and investment costs for renewable energy infrastructure. The model also incorporates constraints related to capacity limitations, demand satisfaction, material flow balance, and renewable energy generation potential.

3.2. 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) [10-15].

Figure 3: Solution approach.

4. Results and discussion

This section presents a case study to demonstrate the effectiveness of the proposed RACLSCND framework and RSO model. The case study considers a home appliance supply chain with a network of potential manufacturing facilities, suppliers, and customer markets.

Data on demand, production costs, transportation costs, facility capacities, renewable energy potential, and collection/remanufacturing costs is collected for each element in the network. Additionally, historical data or expert judgment is used to estimate disruption probabilities for different scenarios (e.g., natural disasters, economic downturn).

Multiple demand scenarios are created to represent potential disruptions. These scenarios may involve fluctuations in demand at specific customer markets or disruptions affecting particular suppliers or facilities. The probability of each scenario occurring is also defined.

The RSO model is implemented in a mathematical programming software package like Gurobi or CPLEX. The collected data and defined scenarios are used to populate the model parameters. The model is then solved to obtain the optimal design of the RACLSCND network.

The solution from the RSO model provides insights into the optimal configuration of the supply chain network. This includes:

- **Facility location:** The model identifies the optimal locations for open production, collection, and remanufacturing facilities.
- **Capacity allocation:** The model determines the optimal production quantities at each open facility.
- **Material flow:** The model specifies the optimal flow of raw materials, finished products, and used products between different network elements under each demand scenario.
- **Renewable energy integration:** The model indicates the facilities where renewable energy sources should be implemented.

The analysis of these results focuses on several key performance indicators (KPIs) such as:

- **Total cost:** This measures the overall cost of operating the supply chain network, including production, transportation, collection, remanufacturing, and investment costs for renewable energy.
- **Carbon footprint:** This metric assesses the environmental impact of the network by considering energy consumption and greenhouse gas emissions.
- **Supply chain resilience:** This indicator evaluates the network's ability to withstand disruptions and maintain customer satisfaction under different demand scenarios.
- **Agility:** This metric measures the network's flexibility to adapt to changing market demands or unexpected events.

By applying the RSO model to the home appliance supply chain case study, the following potential outcomes can be observed:

- The model might recommend opening manufacturing facilities in locations with access to renewable energy sources and lower production costs.
- The network design might involve strategically located collection centers to gather used appliances for remanufacturing.
- The model might suggest allocating production capacity across multiple facilities to enhance redundancy and mitigate the impact of disruptions at individual sites.
- The results might indicate the optimal mix of using renewable energy sources and traditional grid-based electricity at different facilities.

The specific results will depend on the input data and chosen scenarios. However, the case study demonstrates the effectiveness of the RACLSCND framework and RSO model in designing a supply chain network that is resilient, agile, closed-loop, and minimizes its environmental impact.

Table 1. Number of indices, cost function of the case study.

Problem	$\|I\|\|M\|\|C\|\|U\|\|P\|\|T\|\|S\|$	Cost (Dollar)	Activation Renewable energy	Time (second)
Main model	3.3.3.3.3.3.3.3.3.3.3	92397.761	Active	0.209

Table 2. Final locations for RACLSCND.

Variables	City		
Supplier (li_i)	Mashhad 0	Gilan 1	Tabriz 1
Manufacturer (lm_m)	Sanandaj 0	Tehran 1	Mashhad 1
Collection (lu_u)	Sanandaj 0	Tehran 1	Mashhad 1

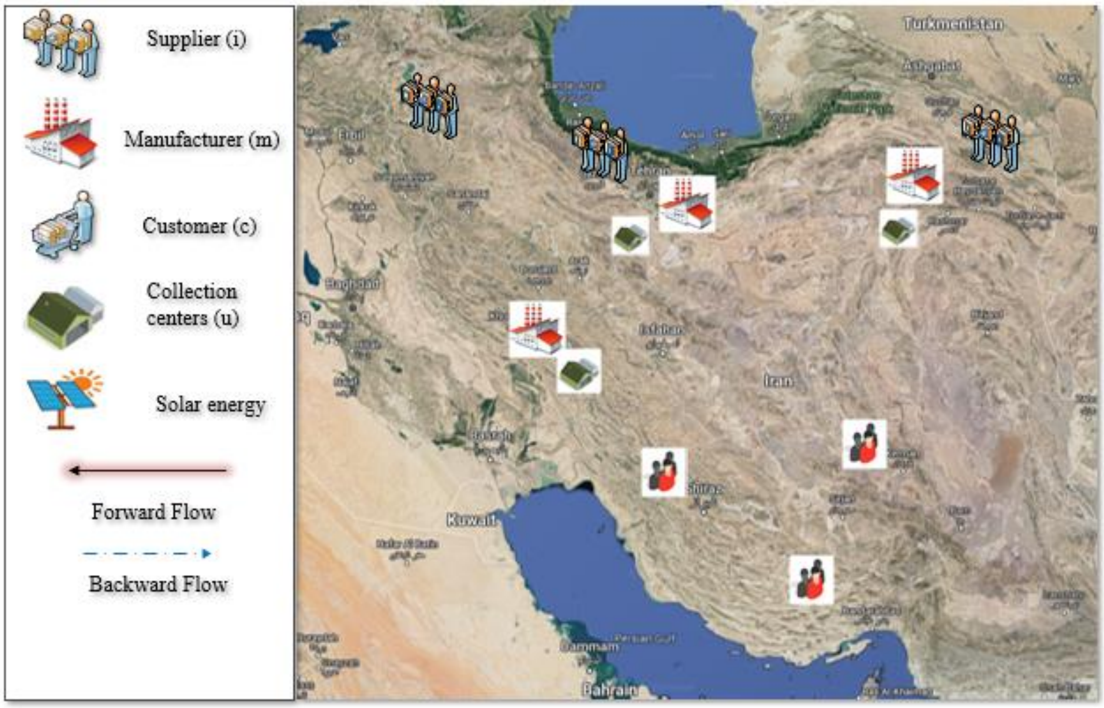

Figure 4: Facility components.

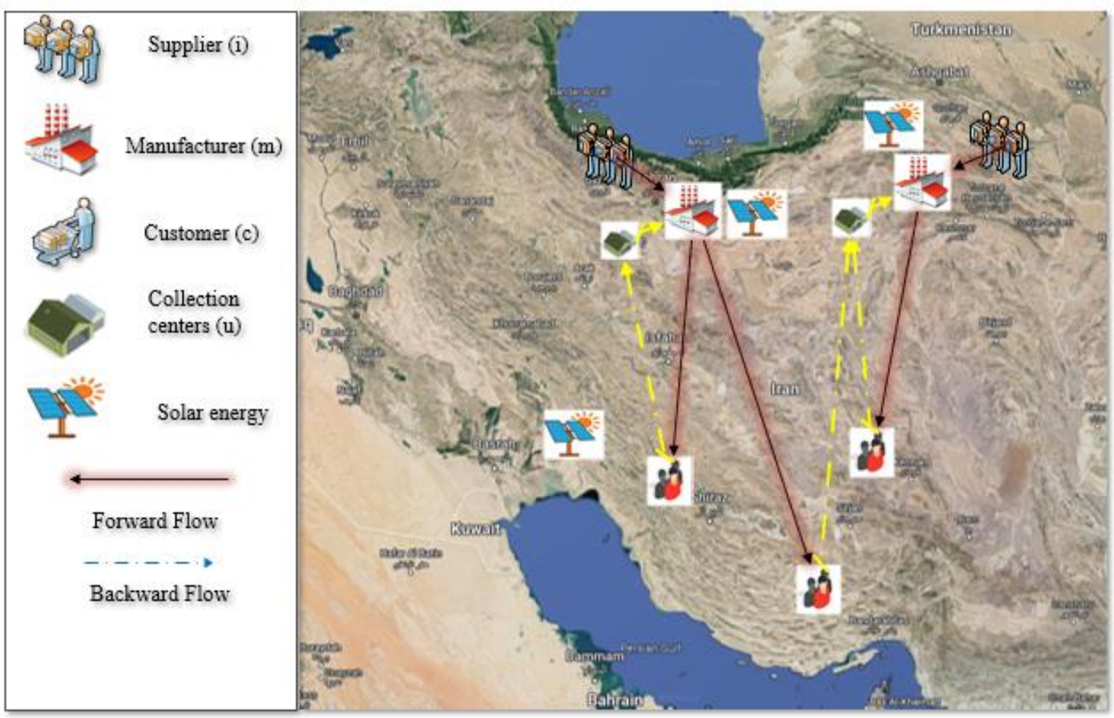

Figure 5: Results of RACLSCND.

4.1. Analysis of agility factor

In this section, the agile factor (δ) is changed between 80% to 100%. As can be seen, varying the agile factor increases cost function (see Table 6, Figure 9 and Figure 10). It is considered that when the agile factor increases, the mathematical model wants to increase responsibility. As a result, the cost function increases.

Table 3. Number of indices, cost function of the case study.

Problem	Agile factor (δ)	Cost (Dollar)	Activation Renewable energy	Time (second)
Main model	80%	92397.76	Active	0.209
	85%	92471.14	Active	0.281
	90%	92544.52	Active	0.165
	95%	92617.89	Active	0.18
	100%	92691.27	Active	0.187

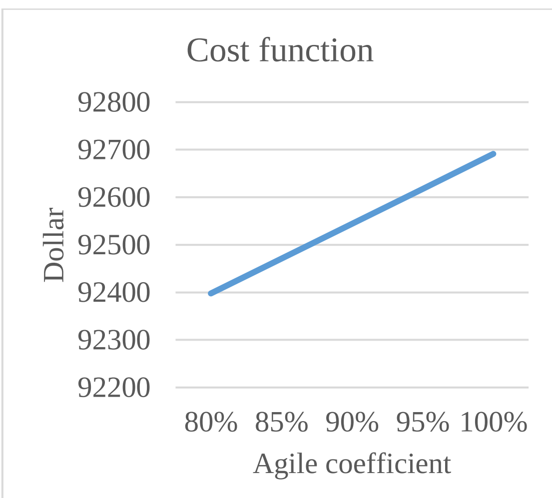

Figure 5: Analysis of agility factor on cost function.

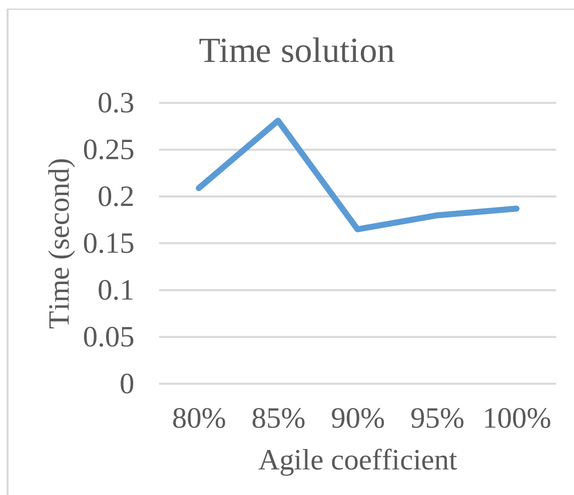

Figure 6: Analysis of agility factor on time solution.

4.2. Analysis of resiliency coefficient

In this section, the resiliency coefficient (Ω) is changed between 60% to 100%. As can be seen, varying the resiliency coefficient increases cost function (see Table 6, Figure 9 and Figure 10). 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. Number of indices, and cost function of the case study.

Problem	Resiliency coefficient (Ω)	Cost (Dollar)	Activation Renewable energy	Time (second)
Main model	30%	47117.89	Active	0.201
	60%	92397.76	Active	0.209
	80%	140141.1	Active	0.175
	90%	140141.1	Active	0.175
	100%	140141.1	Active	0.175

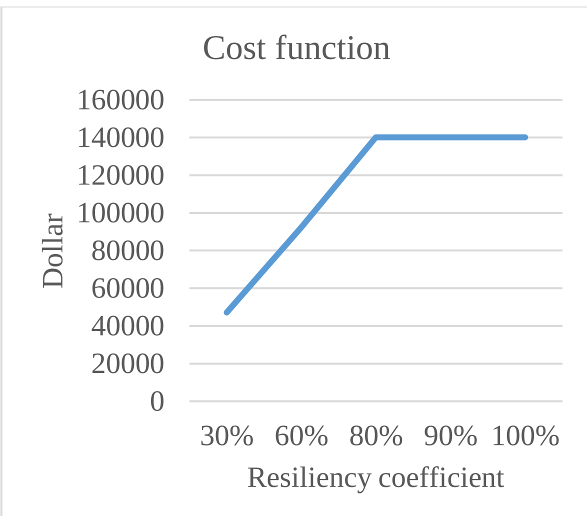

Figure 5: Analysis of agility factor on cost function.

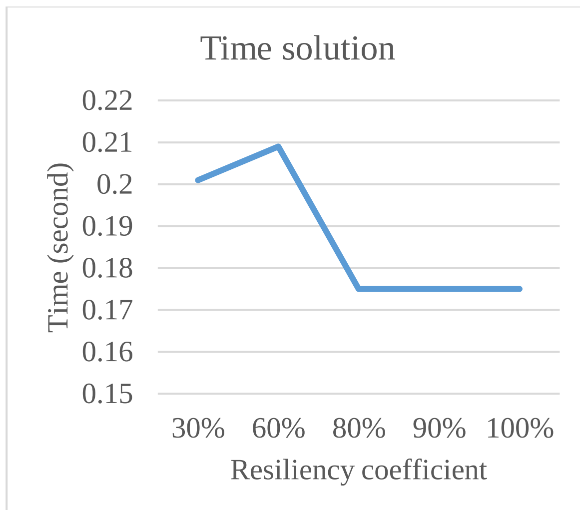

Figure 6: Analysis of agility factor on time solution.

5. Conclusion

This paper has presented a novel approach for designing RACLSCND with renewable energy integration. The proposed RACLSCND framework provides a comprehensive perspective on integrating these critical aspects into SCND. The RSO model has been demonstrated as a valuable tool for optimizing network design while considering multiple objectives and potential disruptions.

The case study results highlight the potential benefits of the RACLSCND approach, including reduced costs, lower carbon footprint, enhanced resilience, and improved agility. This framework offers a promising path towards sustainable and future-proof supply chain management practices.

Future Research:

Further research can explore several avenues to extend this work:

- Developing more sophisticated disruption scenarios to incorporate a wider range of potential risks.
- Incorporating dynamic pricing models to account for fluctuating energy costs and market demands.
- Investigating the application of the RACLSCND framework to different industry sectors.
- Exploring the integration of machine learning and artificial intelligence techniques for real-time optimization and decision-making within the supply chain network.

By continuing research in these areas, the RACLSCND framework can be further refined and its practical applications can be expanded to contribute to a more sustainable and resilient future for global supply chains.

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