Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Multi-Period Sustainable Healthcare Supply Chain Network Design: A Mixed-Integer Linear Programming Approach

Abdulhadi A. Altherwi

aaaltherwi@jazanu.edu.sa

Jazan University

Research Article

Keywords: Healthcare supply chain, Mixed-integer linear programming, Sustainable network design, Carbon emissions, Multi-period optimization.

Posted Date: September 17th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10582699/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Multi-Period Sustainable Healthcare Supply Chain Network Design: A Mixed-Integer Linear Programming Approach

Abdulhadi A. Altherwi

Department of Industrial Engineering, College of Engineering and Computer Sciences, Jazan University, Jazan, Saudi Arabia
aaaltherwi@jazanu.edu.sa

Abstract

Healthcare supply chains must reconcile cost efficiency, environmental sustainability, and uninterrupted service, yet most existing models address these objectives in isolation or within single-period settings. This study develops a multi-period mixed-integer linear programming (MILP) model for sustainable healthcare supply chain network design that integrates supplier allocation, production planning, warehouse activation, inventory management, transportation flows, and shortage minimization within a single optimization framework. Environmental sustainability is embedded through transportation carbon-emission limits, while service quality is enforced through demand-satisfaction, safety-stock, and critical-product service-level constraints. Supplier diversification and budget restrictions are incorporated to strengthen resilience and financial feasibility. The model is implemented in Python and solved with the CBC solver through the PuLP library over a four-period, multi-product, four-echelon network of suppliers, processing centers, warehouses, and hospitals. Under baseline conditions the model attains a 100% service level with zero shortages, opens all three candidate warehouses, generates 526.45 emission units, and uses only 26.32% of the available budget. Sensitivity analysis over a -20% to +20% demand range shows full robustness up to a 10% demand increase, beyond which capacity limits induce shortages. The framework provides decision-makers with a transparent and interpretable tool for sustainable healthcare logistics planning.

Keywords

Healthcare supply chain; Mixed-integer linear programming; Sustainable network design; Carbon emissions; Multi-period optimization.

1. Introduction

Healthcare systems worldwide face mounting challenges in maintaining efficient and reliable supply chain operations as a result of growing demand uncertainty, resource limitations, frequent disruptions, and rising sustainability expectations. Healthcare supply chains differ substantially from conventional commercial supply chains because their performance directly influences patient care quality, public-health outcomes, and operational continuity. The timely delivery of medicines, pharmaceuticals, protective equipment, and other critical materials is essential for uninterrupted clinical services and for limiting operational and clinical risk.

Recent events, including the COVID-19 pandemic, natural disasters, and large-scale supply disruptions, have exposed the vulnerability of healthcare logistics systems and underscored the need for resilient and sustainable network structures. Simulation-based analyses of epidemic outbreaks showed how quickly demand surges and facility disruptions propagate through medical supply networks (Ivanov 2020), while decision-support studies demonstrated the value of proactive demand management during the COVID-19 outbreak (Govindan et al. 2020). Structured reviews of the pandemic period have since called for supply chains that are simultaneously responsive, resilient, and sustainable (Queiroz et al. 2022; Remko 2020; Spieske and Birkel 2021).

In parallel, environmental considerations associated with logistics activities, and in particular carbon emissions generated by transportation, have become increasingly important in supply chain decision-making. Sustainable supply chain management integrates economic, environmental, and social dimensions into network design rather than treating them as afterthoughts (Seuring and Muller 2008). For healthcare logistics, embedding environmental limits alongside service requirements is now regarded as a core design objective rather than an optional extension.

Traditional healthcare supply chain models have primarily focused on minimizing operational cost while overlooking sustainability and service-quality objectives. However, cost minimization alone may yield solutions that reduce system resilience, increase shortage risk, or degrade service quality. Healthcare decision-makers therefore require frameworks capable of balancing multiple operational and strategic objectives at once, integrating economic efficiency with environmental sustainability and reliable service delivery.

Although a wide range of optimization techniques has been applied to supply chain network design, including linear and mixed-integer programming, stochastic and robust optimization, and metaheuristics (Melo et al. 2009; Govindan et al. 2017), several limitations persist for healthcare applications. First, many studies consider only single-period planning environments that cannot represent the dynamic nature of healthcare operations. Second, numerous approaches address transportation and inventory decisions in isolation, without jointly considering facility activation and sustainability factors. Third, environmental constraints such as carbon-emission ceilings and budget restrictions are frequently omitted from healthcare logistics models.

To address these limitations, this study proposes a multi-period sustainable healthcare supply chain network design model formulated as a mixed-integer linear program (MILP). The framework simultaneously determines supplier allocation, production planning, warehouse activation, inventory management, transportation flows, and shortage minimization, while explicitly enforcing service-level, safety-stock, supplier-diversification, carbon-emission, and budget requirements across a four-echelon network of suppliers, processing centers, warehouses, and hospitals.
The proposed model contributes to the literature in several ways: (i) a multi-period network structure is developed to capture dynamic operational behavior; (ii) strategic and operational decisions are integrated within a single optimization framework; (iii) environmental sustainability is incorporated through transportation carbon-emission constraints; (iv) service quality is strengthened through demand-satisfaction requirements, safety-stock policies, and critical-product service-level constraints; (v) resilience is improved through supplier diversification and warehouse-activation decisions; and (vi) a systematic sensitivity analysis evaluates model robustness under varying demand conditions.

The remainder of this paper is organized as follows. Section 2 reviews related literature on healthcare and sustainable supply chain network design. Section 3 presents the methodology, including model assumptions and the complete mathematical formulation. Section 4 reports and discusses the optimization results, and Section 5 presents the sensitivity analysis. Section 6 outlines the limitations of the study, Section 7 concludes, and Section 8 identifies directions for future research.

2. Literature Review

Research on supply chain network design (SCND) for healthcare sits at the intersection of several established streams: sustainable network design, healthcare and pharmaceutical logistics, vaccine and blood supply chains, facility-location and inventory integration, and resilience under disruption. This section reviews these streams and positions the present study within them.

2.1 Sustainable supply chain network design

Sustainability has become an intrinsic element of modern network design, with models increasingly embedding environmental and social objectives alongside cost. Comprehensive reviews confirm that economic, environmental, and social pillars are now routinely integrated into SCND optimization (Seuring and Muller 2008; Govindan et al. 2017). A large body of work formulates these problems as multi-objective mixed-integer programs. Arampantzi and Minis (2017) proposed a multi-objective model for sustainable network design and applied it to a global manufacturer, while Vali-Siar and Roghanian (2022) developed a responsive, resilient, and sustainable mixed open- and closed-loop network under hybrid uncertainty. Sabouhi et al. (2021) combined sustainability and resilience with regional considerations, and Kumar and Kumar (2024) explicitly linked greenhouse-gas regulation to total supply chain cost. Solution strategies range from exact methods to metaheuristics; Zhang et al. (2023) applied a chaotic particle-ant colony algorithm to a three-objective sustainable network, and Guo et al. (2022) studied lateral collaboration with cost-sharing in sustainable optimization. Closed-loop and reverse structures have also received sustained attention, including the foundational reverse-logistics models of Fleischmann et al. (1997), the spanning-tree genetic-algorithm formulation of Wang and Hsu (2010), the cross-docking design of Rezaei and Kheirkhah (2018), and the comprehensive review of closed-loop supply chains by Govindan et al. (2015).

2.2 Healthcare and pharmaceutical supply chains

Healthcare-specific network design has expanded rapidly, particularly since the COVID-19 pandemic exposed weaknesses in medical-product availability and distribution responsiveness. Goodarzian et al. (2021a) developed an integrated sustainable medical supply chain network during COVID-19 that jointly optimized production, distribution, inventory, allocation, and location decisions in a multi-period structure, a work closely related to the present study. Ala et al. (2024) proposed a fuzzy multi-objective sustainable healthcare network incorporating economic, environmental, and social objectives. Mathematical programming has been applied extensively to pharmaceutical and medicine networks: Goodarzian et al. (2021b) considered production-technology policy with novel heuristics, Goodarzian et al. (2021c) designed a green medicine network under uncertainty integrating allocation, location, production, distribution, routing, inventory, and purchasing, and Halim et al. (2019) presented a decision-support framework for sustainable pharmaceutical network design. Hansen and Grunow (2015) balanced time-to-market and risk before product launch.

A complementary stream emphasizes pharmaceutical inventory and perishability. Savadkoohi et al. (2018) proposed a possibilistic multi-period location-inventory model for perishable pharmaceuticals, and Zandkarimkhani et al. (2020) used chance-constrained fuzzy goal programming for the same problem class. Tat et al. (2020) modeled pharmaceutical coordination through reselling in alternative markets, while Sazvar et al. (2021) designed a sustainable closed-loop pharmaceutical chain addressing demand uncertainty, brand, and waste. At the hospital level, Ahmadi et al. (2022) introduced reinforcement-learning inventory policies for perishable products, Zwaida et al. (2021) and Saedi et al. (2016) optimized inventory to prevent drug shortages, and Sohrabi et al. (2021) addressed equitable allocation of processed corneal tissue. Cold-chain requirements add further complexity, as shown by Golestani et al. (2021) for multi-temperature perishable distribution. More recent contributions broaden the scope of healthcare logistics: Goodarzian and Ghasemi (2025) integrated electric vehicles and charging-station decisions through simulation-optimization, Tao et al. (2025) formulated a mixed-integer SPD model for medical consumables, Ariningsih et al. (2025) addressed supply frequency, equity, and waste in essential-medicine distribution, and Hajipour Machiani et al. (2025) designed a sustainable network for producing and distributing personal protective equipment.

2.3 Vaccine, blood, and medical-waste logistics

Product-specific healthcare networks form a distinct and active stream. In vaccine logistics, Georgiadis and Georgiadis (2021) formulated a MILP for optimal COVID-19 vaccine supply-chain planning, Chowdhury et al. (2022) modeled a sustainable vaccine chain for a developing economy considering cost, emissions, and employment, and Gilani and Sahebi (2022) developed a data-driven robust model addressing vaccine-access uncertainty. Goodarzian et al. (2022) proposed a sustainable-resilience healthcare network for handling the pandemic. Reverse logistics and waste management are equally critical because medical waste, expired pharmaceuticals, and vaccine-related waste create environmental and public-health risks: Bani et al. (2022) designed a reverse network for COVID-19 vaccine waste under uncertainty, Govindan et al. (2022) proposed a green reverse-logistics network for medical waste, Nosrati-Abarghooee et al. (2023) addressed healthcare-waste reverse logistics under epidemic conditions, and Tirkolaee et al. (2021) solved a sustainable location-routing problem for medical waste during the outbreak.

Blood supply chains, a special case of humanitarian logistics, have a long modeling tradition beginning with the location-allocation model of Or and Pierskalla (1979) and the hierarchical perspective of Pierskalla (2005). Sahin et al. (2007) proposed mixed-integer location sub-models for regional blood services, while structured reviews by Belien and Force (2012) and Osorio et al. (2015) consolidated quantitative blood-supply models. Disaster-oriented designs include the robust dynamic model of Jabbarzadeh et al. (2014), the efficient-and-effective design of Fahimnia et al. (2017), the centralization analysis of Hosseinifard and Abbasi (2018), the multi-stage stochastic platelet model of Xu and Szmerekovsky (2023), the evolutionary multi-objective model of Hsieh (2014), and the recent review of Meneses et al. (2023); more recently, Rekabi et al. (2024) designed a responsive, sustainable, and resilient blood supply chain network under uncertainty and disruption. More broadly, humanitarian and emergency logistics have produced influential pre-positioning and relief-allocation models (Rawls and Turnquist 2011; Rottkemper et al. 2011; Mete and Zabinsky 2010; Nayeri et al. 2018; Yang et al. 2023), which inform the service-continuity orientation of healthcare network design.

2.4 Facility location and inventory integration

The structural backbone of healthcare network design draws on classical facility-location and location-inventory theory. Comprehensive reviews establish the modeling landscape for distribution-system design and facility location

under uncertainty (Klose and Drexl 2005; Melo et al. 2009; Snyder 2006), and recent reviews extend this landscape to financial considerations in network design (Jahani et al. 2024). A particularly relevant line of work integrates location with inventory decisions: Daskin et al. (2002) and Shen et al. (2003) formulated joint location-inventory models that capture the trade-off between facility fixed costs and stock pooling, while the perishable-inventory theory of Nahmias (1982) remains foundational for medical products with limited shelf life. Multi-echelon and multi-period MILP formulations extend these ideas to realistic operating conditions: Gendron and Semet (2009) developed formulations and relaxations for a multi-echelon capacitated location-distribution problem, Kchaou Boujelben et al. (2016) addressed multi-period facility location under multiple operational constraints, Kratica et al. (2014) proposed a new MILP for multi-level uncapacitated location, and Hajipour et al. (2016) tackled congested facility location-allocation with Pareto-based metaheuristics. Reviews of integrated production-distribution planning (Kumar et al. 2020) and standard treatments of integer programming and supply chain planning (Wolsey 2020; Chopra and Meindl 2016) provide the methodological grounding for the formulation adopted here.

2.5 Resilience, disruption, and carbon-aware design

Network resilience under disruption is a recurring theme, intensified by the pandemic. Reliability-oriented models explicitly account for facility and transportation failures (Peng et al. 2011; Azad et al. 2013), whereas pandemic-era studies emphasize agility and responsiveness in logistics (Ivanov 2020; Govindan et al. 2020; Choi 2020) and map research agendas for resilient, technology-enabled supply chains (Queiroz et al. 2022; Remko 2020; Spieske and Birkel 2021). A parallel stream embeds environmental limits directly into network optimization: Diabat and Simchi-Levi (2009) introduced a carbon-capped network design problem, and Elhedhli and Merrick (2012) minimized emissions jointly with cost. The present study aligns with both streams by combining supplier diversification and warehouse-activation decisions for resilience with explicit transportation carbon-emission limits for sustainability.

2.6 Research gap and positioning

Despite these contributions, several gaps remain. First, many studies focus on a single product class, such as vaccines, blood, PPE, or medical waste, while comparatively few integrate multiple healthcare product categories within one network. Second, models that emphasize sustainability often do not jointly combine emission limits with budget restrictions, warehouse-opening decisions, inventory balance, safety stock, shortage penalties, and service-level requirements. Third, several approaches rely on advanced metaheuristics, fuzzy programming, or simulation-optimization that, while powerful, can reduce transparency and interpretability for practitioners. The present study addresses these gaps by developing a transparent multi-period MILP that jointly optimizes supplier allocation, processing, warehouse activation, inventory, transportation, and shortage minimization, subject to carbon-emission, budget, safety-stock, cold-chain, supplier-diversification, and critical-product service-level constraints, and by evaluating robustness through systematic sensitivity analysis.

3. Methodology

This study proposes a multi-period sustainable healthcare supply chain network design framework formulated as a mixed-integer linear program (MILP). The model determines strategic and operational decisions simultaneously while balancing economic, environmental, and service-related objectives. The healthcare supply chain is structured as a four-echelon network comprising suppliers, processing centers, warehouses, and hospitals. Material flows are routed from suppliers to processing centers, from processing centers to warehouses, and finally from warehouses to hospitals. Unlike traditional cost-minimization models, the proposed framework jointly incorporates inventory management, warehouse activation, shortage minimization, carbon-emission limits, service-level requirements, and budget restrictions across multiple products and planning periods. The overall research framework is illustrated in Figure 1.

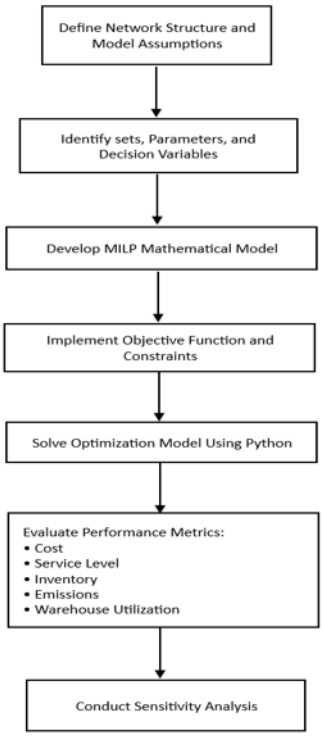


Figure 1. Proposed methodological framework of the sustainable healthcare supply chain optimization model.

3.1 Model assumptions

To preserve practical applicability while keeping the formulation tractable, the following assumptions are adopted:

- Hospital demand is known and deterministic within each planning period.
- Supplier capacities remain constant throughout the planning horizon.
- Production capacities at processing centers are predefined and limited.
- Warehouse storage capacities are fixed during the planning periods.
- Transportation capacities between supply chain stages are limited.
- Inventory shortages are permitted but incur penalty costs.
- Warehouse opening decisions are modeled as binary variables.
- Carbon emissions are generated by transportation activities across all network stages.
- Safety stock levels are maintained for critical healthcare products.
- Cold-chain compatibility requirements govern temperature-sensitive products.
- A budget constraint limits total operational expenditure in each period.

3.2 Notation

The sets, parameters, and decision variables used in the proposed model are summarized in Tables 1, 2, and 3, respectively.

Table 1. Sets used in the proposed model.

Sets	Description
$\boldsymbol{S}$	Set of suppliers
$\boldsymbol{P}$	Set of processing centers
$\boldsymbol{W}$	Set of warehouses
$\boldsymbol{H}$	Set of hospitals
$\boldsymbol{K}$	Set of products

T	Set of time periods
K_C	Cold-chain products
K_{cr}	Critical products

Table 2. Parameters used in the proposed model.

Parameters	Description
D_{hkt}	Demand of hospital h for product k in period t
$SC_{ap_{skt}}$	Supply capacity of supplier s
$PC_{ap_{pkt}}$	Production capacity at center p
$WC_{ap_{wt}}$	Warehouse capacity
$RC_{ap_{ht}}$	Receiving capacity at hospital
$TC_{ap_{spt}^{SP}}, TC_{ap_{pwt}^{PW}}, TC_{ap_{wht}^{WH}}$	Transportation capacities
F_w	Fixed cost of opening warehouse
$C^{sup}, C^{pro}, C^{sp}, C^{pw}, C^{wh}, C^{inv}, C^{short}$	Cost parameters
e^{sp}, e^{pw}, e^{wh}	Emission coefficients
E_t^{max}	Emission limit
SS_{wk}	Safety stock level
α_k	Service level for critical products
β_{sk}	Supplier diversification parameter
B_t	Budget limit
$Cold_w, Cold_h$	Cold-chain compatibility
M_w	Large constant

Table 3. Decision variables used in the proposed model.

Decision variables	Description
X_{sptk}	Flow from supplier to processing center
Y_{pwtk}	Flow from processing center to warehouse
Z_{whtk}	Flow from warehouse to hospital
I_{wkt}	Inventory level
Q_{pkt}	Production quantity
$Short_{hkt}$	Unmet demand
$u_w \in \{0, 1\}$	Warehouse activation

3.3 Mathematical model

The objective function, Equation (1), minimizes the total healthcare supply chain cost. It aggregates the warehouse opening cost, the transportation costs incurred across the supplier-to-processing, processing-to-warehouse, and warehouse-to-hospital stages, the supplier procurement cost, the processing cost, the inventory holding cost, and the shortage penalty cost.

$$\boldsymbol{Min}\ \sum_{w\in W} f_w u_w + \sum_{s\in S}\sum_{p\in P}\sum_{k\in K}\sum_{t\in T} C_{sptk}^{sp} X_{sptk} + \sum_{p\in P}\sum_{w\in W}\sum_{k\in K}\sum_{t\in T} C_{pwtk}^{pw} Y_{pwtk} + \sum_{w\in W}\sum_{h\in H}\sum_{k\in K}\sum_{t\in T} C_{whkt}^{wh} Z_{whtk} + \sum_{s\in S}\sum_{k\in K}\sum_{t\in T} C_{skt}^{sup}\left(\sum_{p\in P} X_{sptk}\right) +$$

$$\sum_{p\in P}\sum_{k\in K}\sum_{t\in T} C^{proc}_{pkt} Q_{ptk} + \sum_{w\in W}\sum_{k\in K}\sum_{t\in T} C^{inv}_{wkt} I_{wkt} + \sum_{h\in H}\sum_{k\in K}\sum_{t\in T} C^{short}_{hkt} Short_{hkt} \quad (1)$$

$$\sum_{w\in W} Z_{whtk} + Short_{hkt} = D_{hkt} \qquad \forall\, h \in H, k \in K, t \in T \quad (2)$$

$$\sum_{w\in W} Z_{whtk} \geq \alpha_k D_{hkt} \quad \forall\, h \in H, k \in K, t \in T \quad (3)$$

Equation (4) restricts the quantity shipped from each supplier to its available supply capacity in every period.

$$\sum_{p\in P} X_{sptk} \leq SC_{ap_{skt}} \qquad \forall\, s \in S, k \in K, t \in T \quad (4)$$

Constraints (5)-(7) describe production at the processing centers: the processed quantity cannot exceed the inbound supply (5) or the production capacity of the center (6), and outbound flows to warehouses cannot exceed the processed quantity (7).

$$Q_{pkt} \leq X_{sptk} \quad \forall\, p \in P, k \in K, t \in T \quad (5)$$

$$Q_{pkt} \leq PC_{ap_{pkt}} \quad \forall\, p \in P, k \in K, t \in T \quad (6)$$

$$\sum_{w\in W} Y_{pwtk} \leq Q_{pkt} \qquad \forall\, p \in P, k \in K, t \in T \quad (7)$$

The inventory balance Equations (8) and (9) link inventory levels across consecutive periods. Equation (8) initializes the first-period inventory from the opening stock, while Equation (9) propagates inventory in the remaining periods as a function of inbound and outbound warehouse flows.

$$I_{wk1} = I^0_{wk} + \sum_{p\in P} Y_{pw1k} - \sum_{h\in H} Z_{wh1k} \qquad \forall\, w, k \quad (8)$$

$$I_{wkt} = I_{wk,t-1} + \sum_{p\in P} Y_{pwtk} - \sum_{h\in H} Z_{whtk} \quad \forall\, w \in W, k \in K, t \in T \quad (9)$$

Warehouse capacity and activation are enforced by Constraints (10)-(12). Stored inventory cannot exceed the capacity of an opened warehouse (10), and both inbound (11) and outbound (12) flows are admitted only through warehouses that are opened.

$$\sum_{k\in K} I_{wkt} \leq WC_{ap_{wt}} U_w \quad \forall\, w \in W, t \in T \quad (10)$$

$$\sum_{p\in P}\sum_{k\in K} Y_{pwtk} \leq M_w U_w \qquad \forall\, w \in W, t \in T \quad (11)$$

$$\sum_{h\in H}\sum_{k\in K} Z_{whtk} \leq M_w U_w \qquad \forall\, w \in W, t \in T \quad (12)$$

Transportation capacity limits on the three network stages are imposed by Constraints (13)-(15), which bound the shipped quantities between suppliers and processing centers, processing centers and warehouses, and warehouses and hospitals, respectively.

$$\sum_{k\in K} X_{sptk} \leq TC_{ap^{SP}_{spt}} \quad \forall\, s \in S, p \in P, t \in T \quad (13)$$

$$\sum_{k\in K} Y_{pwtk} \leq TC_{ap^{PW}_{pwt}} \quad \forall\, p \in P, w \in W, t \in T \quad (14)$$

$$\sum_{k\in K} Z_{whtk} \leq TC_{ap^{WH}_{wht}} \quad \forall\, w \in W, h \in H, t \in T \quad (15)$$

Equation (16) limits the total quantity received by each hospital to its receiving and handling capacity.

$$\sum_{w\in W}\sum_{k\in K} Z_{whtk} \leq RC_{ap_{ht}} \quad \forall\, h \in H, t \in T \quad (16)$$

Safety-stock availability for critical healthcare products is guaranteed by Equation (17).

$$I_{wkt} \geq SS_{wk} \quad \forall\, w \in W, k \in K, t \in T \tag{17}$$

Cold-chain compatibility is enforced by Constraints (18) and (19), which allow temperature-sensitive products to be stored and transported only through cold-chain-compatible warehouses and hospitals.

$$I_{wkt} \leq WC_{ap_{wt}} * Cold_w \quad \forall\, w \in W, k \in K, t \in T \tag{18}$$

$$Z_{whtk} \leq TC_{ap_{wht}^{WH}} * Cold_h \quad \forall\, w \in W, h \in H, k \in K, t \in T \tag{19}$$

To avoid over-reliance on a single supplier and to improve supply chain resilience, the supplier diversification Constraint (20) caps the share that can be allocated to any individual supplier.

$$\sum_{p \in P} X_{sptk} \leq \beta_{sk} \sum_{s' \in S} \sum_{p \in P} X_{S'ptk} \quad \forall\, s \in S, k \in K, t \in T \tag{20}$$

Environmental sustainability is incorporated through Equation (21), which limits the total carbon emissions generated by transportation activities in each period to a predefined emission cap.

$$\sum_{s,p,k} e_{sptk}^{sp} X_{sptk} + \sum_{p,w,k} e_{pwtk}^{pw} Y_{pwtk} + \sum_{w,h,k} e_{whtk}^{wh} Z_{whtk} \leq E_t^{max} \quad \forall\, t \in T \tag{21}$$

Finally, the budget Constraint (22) ensures that the total operational expenditure - covering procurement, processing, transportation, and inventory holding - remains within the available financial resources in each period.

$$\sum_{s,p,k} C_{sptk}^{sp} X_{sptk} + \sum_{p,w,k} C_{pwtk}^{pw} Y_{pwtk} + \sum_{w,h,k} C_{whtk}^{wh} Z_{whtk} + \sum_{p,k} C_{pkt}^{proc} Q_{pkt} + \sum_{w,k} C_{wkt}^{inv} I_{wkt} \leq B_t \quad \forall\ t \in T \tag{22}$$

Constraints (23) and (24) define the decision-variable domains: continuous non-negativity for the flow, inventory, production, and shortage variables, and a binary restriction for the warehouse activation variables.

$$X_{sptk}, Y_{pwtk}, Z_{whtk}, I_{wkt}, Q_{pkt}, Short_{hkt} \geq 0 \tag{23}$$

$$U_w \in \{0, 1\} \tag{24}$$

3.4 Solution procedure

The proposed MILP model was implemented in Python and solved using the CBC (Coin-or Branch and Cut) solver through the PuLP optimization library. The complete solution procedure consisted of the following steps:

1. Initialize the model parameters and datasets, including demand, capacities, cost coefficients, emission factors, and budget limits.
2. Define the decision variables for supplier, processing, warehouse, and hospital flows, inventory, production, shortage, and warehouse activation.
3. Implement the objective function that minimizes total supply chain cost.
4. Formulate the operational constraints governing demand fulfilment, capacity, inventory balance, service level, cold chain, supplier diversification, emissions, and budget.
5. Solve the resulting mixed-integer linear program with the CBC solver.
6. Extract the optimal decision values and objective value.
7. Compute performance indicators and generate the supporting visualizations.
8. Conduct the demand-based sensitivity analysis to evaluate network robustness.

4. Results and Discussion

4.1 Overview of optimization results

The proposed multi-period sustainable healthcare supply chain network design model was solved to optimality, indicating that all constraints and decision-variable requirements were satisfied within the specified operational limits. The model simultaneously determined supplier allocation, production planning, warehouse activation, inventory levels, transportation flows, shortage quantities, carbon emissions, and budget utilization. The results confirm that the framework can achieve operational efficiency while preserving environmental and economic sustainability. The optimal solution status is shown in Figure 2.

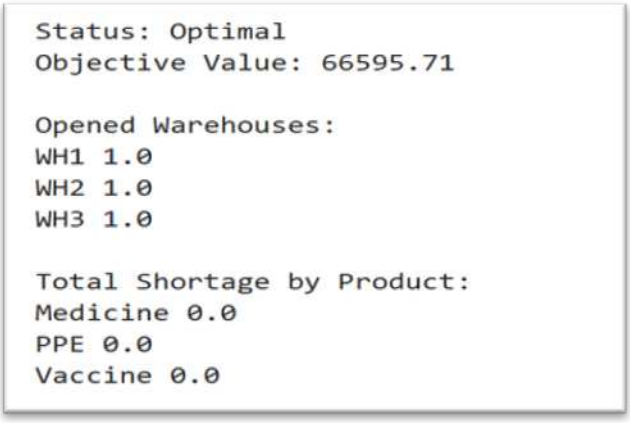


Figure 2. Optimal solution status of the proposed model.

4.2 Warehouse opening decisions

The optimization results indicate that all three candidate warehouses (WH1, WH2, and WH3) were opened, as summarized in Table 4. This outcome suggests that the demand across hospitals and planning periods required the use of all available facilities to maintain efficient distribution and service continuity. Operationally, using all warehouses shortens delivery distances and improves responsiveness; strategically, it increases network flexibility and reduces exposure to supply disruption. The model did not close any warehouse because doing so would have increased transportation cost and degraded service performance.

Table 4. Warehouse opening decisions.

Warehouse	Decision
WH1	Open
WH2	Open
WH3	Open

4.3 Demand fulfilment and service-level analysis

Across all hospitals and products, the total demand was 4,091 units and the total delivered quantity was also 4,091 units, with zero shortage; the overall service level achieved by the model was therefore 100%, as reported in Table 5. Achieving a 100% service level is particularly significant in healthcare because shortages of medical products directly affect patient care. The absence of shortages indicates that the selected network structure, production capacities, inventory policies, and transportation decisions were jointly sufficient to satisfy demand throughout the planning horizon, and that the shortage penalty effectively steered the model toward complete demand fulfilment.

Table 5. Demand fulfilment performance.

Metric	Value
Total demand (units)	4,091
Delivered quantity (units)	4,091
Shortage (units)	0

Service level (%)	100

4.4 Environmental sustainability performance

The environmental performance of the network was evaluated through the carbon emissions associated with transportation across all stages. Total carbon emissions over the planning horizon were 526.45 emission units, remaining within the imposed emission cap. This result demonstrates that the framework successfully embedded sustainability into supply chain decision-making: rather than optimizing cost in isolation, the model balanced transportation efficiency against environmental impact, distributing flows so as to respect the per-period emission limits while still meeting demand.

4.5 Budget utilization analysis

The average budget utilization across the planning periods was 26.32%, indicating that the total operational cost generated by the optimized network remained well below the available budget. This relatively low utilization reflects strong economic efficiency arising from efficient transportation allocation, balanced warehouse use, well-managed inventory, effective supplier and production planning, and the elimination of unnecessary shortages. From a managerial perspective, the unused budget capacity provides decision-makers with flexibility for future network expansion, emergency preparedness, capacity investment, sustainability initiatives, and risk-mitigation strategies.

4.6 Inventory policy analysis

The total positive ending inventory across warehouses and planning periods was 350 units. The presence of ending inventory indicates that the model deliberately maintained buffer stock to support future demand and operational stability rather than driving inventory to zero. Maintaining positive inventory is particularly important in healthcare, where demand uncertainty and service continuity are critical. The obtained levels show that the model balanced inventory holding cost against shortage penalty cost, retaining reasonable buffers consistent with realistic healthcare logistics practice and the safety-stock requirements for critical products.

4.7 Warehouse capacity utilization analysis

Figure 3 presents the warehouse capacity utilization across the four planning periods for the three opened warehouses. Warehouse 1 (WH1) exhibited the highest utilization, reaching approximately 15.5% in the first period before stabilizing near 8.3% in periods two to four; this pattern suggests that WH1 initially handled a larger volume to establish inventory availability and then maintained a stable operating level. Warehouse 2 (WH2) remained stable at approximately 7.7% throughout, reflecting a balanced and consistent workload, while Warehouse 3 (WH3) maintained the lowest utilization at approximately 4.3%, functioning largely as a supporting facility that preserves reserve capacity for demand surges. Overall, utilization remained low relative to total capacity, indicating that the model distributed activity across facilities without creating bottlenecks and retained spare capacity that improves responsiveness during emergencies.

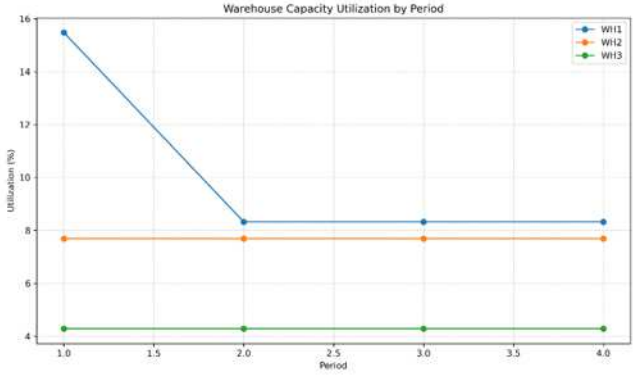


Figure 3. Warehouse capacity utilization across planning periods.

Figure 4 presents the total quantity delivered for each product category over the planning horizon. Personal protective equipment (PPE) represents the largest delivered volume at approximately 1,870 units, followed by medicine at roughly 1,345 units and vaccines at about 870 units, reflecting the differing demand weights of the three product classes.

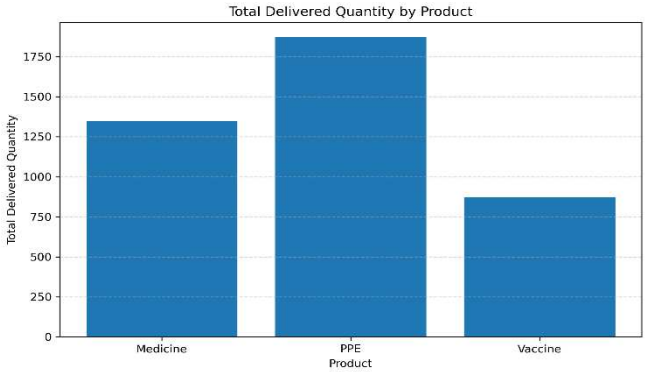


Figure 4. Total delivered quantity by product.

Figure 5 compares total demand with the delivered quantity for each product. For every product category the delivered quantity coincides exactly with demand, visually confirming the 100% service level and zero shortages reported in Section 4.3 under baseline operating conditions.

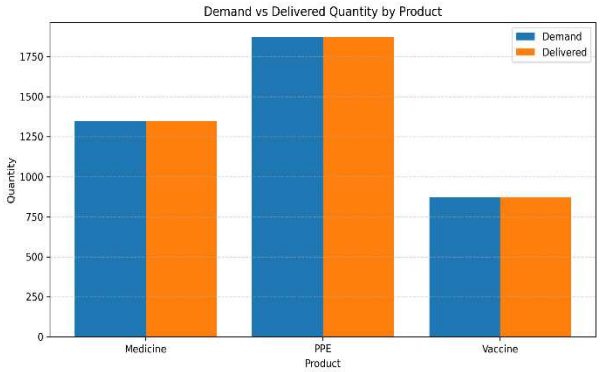


Figure 5. Demand versus delivered quantity by product.

Figure 6 reports the total ending inventory held at each warehouse. Warehouse 1 (WH1) maintains the highest inventory at approximately 170 units, followed by Warehouse 2 (WH2) at about 120 units and Warehouse 3 (WH3) at roughly 60 units. This distribution is consistent with the warehouse-utilization pattern in Section 4.7, where WH1 carries the largest share of distribution activity.

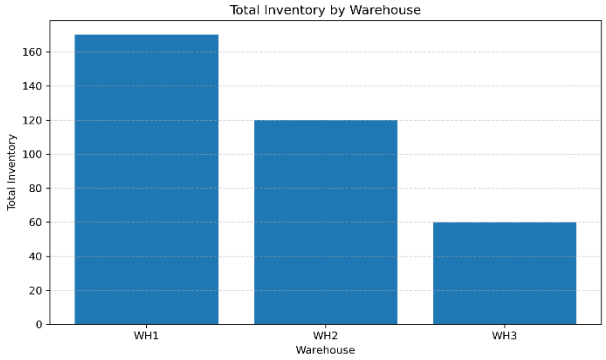


Figure 6. Total ending inventory by warehouse

5. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the robustness and stability of the proposed network under varying demand conditions. Demand was systematically scaled around the baseline scenario to examine the effect of demand fluctuations on operational cost, demand fulfilment, and service quality. Five scenarios were considered: -20%, -10%, baseline, +10%, and +20% demand. The purpose was to assess the ability of the model to maintain performance under both favourable and stressed conditions.

As shown in Table 6, the model retained an optimal and feasible solution in every scenario, confirming strong computational robustness and operational adaptability. Maintaining feasibility under varying demand is especially important in healthcare, where demand uncertainty arises from epidemics, emergencies, and seasonal variation. The objective value increased monotonically with demand, rising from 53,777.05 under the -20% scenario to 84,947.98 under the +20% scenario, because higher demand requires additional procurement, processing, transportation, inventory, and potentially shortage penalties.

Importantly, the cost increase was not perfectly linear. Between baseline and +10% demand the objective rose by approximately 7,457.96, whereas between +10% and +20% the increase grew to approximately 10,894.31. This accelerating growth signals that the network begins to experience operational stress as demand approaches its capacity limits.

Table 6. Demand sensitivity analysis results.

Demand multiplier	Demand change (%)	Status	Objective value	Total demand	Delivered
0.8	-20	Optimal	53,777.05	3,272.8	3,272.8
0.9	-10	Optimal	60,151.72	3,681.9	3,681.9
1.0	0	Optimal	66,595.71	4,091.0	4,091.0
1.1	+10	Optimal	74,053.67	4,500.1	4,440.9
1.2	+20	Optimal	84,947.98	4,909.2	4,556.0

5.1 Service-level performance under demand variations

Service level performance remained at 100% under the reduced and baseline demand scenarios, as reported in Table 7. The network therefore satisfied all healthcare demand under normal operating conditions. When demand increased by 10%, however, the service level fell slightly to 98.68%, and it declined further to 92.81% under the +20% scenario. These reductions indicate that operational constraints become binding at higher demand levels, including supplier-capacity, processing-capacity, warehouse-capacity, transportation, budget, and emission limits. The +10% increase therefore marks the practical operational threshold of the proposed network.

Table 7. Service-level performance under demand changes.

Demand change (%)	Service level (%)
-20	100
-10	100
0	100
+10	98.68
+20	92.81

5.2 Shortage analysis

The shortage analysis in Table 8 provides further insight into network resilience under stress. No shortages occurred under reduced or baseline demand. Once demand exceeded the baseline, however, shortages emerged and grew disproportionately, rising from 59.2 units at +10% demand to 353.2 units at +20% demand. The non-proportional increase suggests bottleneck formation within the network: the system is highly resilient under normal conditions but becomes vulnerable as demand approaches its capacity ceiling.

Table 8. Shortage analysis under demand scenarios.

Demand change (%)	Shortage quantity (units)
-20	0
-10	0
0	0
+10	59.2
+20	353.2

5.3 Managerial implications of the sensitivity analysis

From a managerial perspective, the sensitivity analysis yields several practical findings. The network performs effectively under normal and moderate demand and maintains complete demand satisfaction without shortages at the baseline. Capacity limitations emerge once demand rises beyond approximately 10% above the baseline, which defines the operational threshold of the current configuration. To strengthen resilience beyond this threshold, decision-makers may increase supplier and warehouse capacities, raise safety-stock levels, add emergency suppliers, expand transportation availability, and revisit the budget and emission limits. The relatively low baseline budget utilization reported in Section 4 provides financial headroom for such capacity investments.

6. Limitations of the Study

Despite its contributions, the proposed framework has several limitations that should be acknowledged. First, the study relies on representative numerical data for demand, costs, capacities, and emission parameters; real-world deployment would require calibration with actual operational data from a specific healthcare system. Second, demand and transportation disruptions are not modeled dynamically beyond the predefined scenarios used in the sensitivity analysis, and each planning period is treated as deterministic. Third, the model adopts a single aggregate cost objective with sustainability and service requirements imposed as constraints, rather than an explicit multi-objective formulation that would trace the full trade-off frontier. Finally, vehicle routing, lead-time variability, and facility-disruption risk are abstracted away to preserve linearity and interpretability.

7. Conclusion

This study developed a multi-period sustainable healthcare supply chain network design model based on mixed-integer linear programming to support strategic and operational decision-making in healthcare logistics. The framework integrates supplier allocation, production planning, warehouse activation, inventory management, transportation flows, and shortage minimization within a single optimization structure, while explicitly enforcing service-level, safety-stock, supplier-diversification, cold-chain, carbon-emission, and budget requirements across a four-echelon network of suppliers, processing centers, warehouses, and hospitals.

The computational results demonstrate that the model attains an optimal solution while satisfying all operational constraints. Under baseline conditions it achieves complete demand fulfilment with a 100% service level and zero shortages, opens all three candidate warehouses, maintains total transportation emissions at 526.45 units, retains 350 units of ending inventory as an operational buffer, and uses only 26.32% of the available budget. These outcomes show that operational efficiency, environmental responsibility, and reliable service can be achieved simultaneously. The sensitivity analysis confirms that the network remains fully robust up to a 10% demand increase, beyond which capacity limits induce shortages and service-level decline, thereby identifying a clear operational threshold for capacity planning.

Overall, the proposed framework offers healthcare managers a transparent and interpretable decision-support tool for improving resource allocation, enhancing service quality, reducing operational risk, and advancing sustainable healthcare logistics. Because the formulation is a standard MILP, it remains tractable and explainable, which is valuable for practitioners who must justify capacity, sustainability, and budget decisions to clinical and administrative stakeholders.

8. Future Research Directions

Several extensions could enhance the realism and applicability of the model. Future work may incorporate stochastic or robust demand modeling and explicit facility-disruption risk to capture uncertainty more directly, and may adopt fuzzy parameters where historical data are scarce. Integrating vehicle routing, renewable-energy use, and electric-vehicle transportation would refine the environmental dimension, while reverse-logistics and medical-waste recovery would close the loop on sustainability. Pandemic-response and emergency-logistics scenarios, artificial-intelligence-based demand forecasting, and resilience- and disruption-management mechanisms represent further promising directions. Finally, future studies could reformulate the problem as an explicit multi-objective program and compare exact optimization with metaheuristic approaches such as genetic algorithms, particle swarm optimization, and NSGA-II to address larger problem instances.

References

Ahmadi, E., Mosadegh, H., Maihami, R., Ghalehkhondabi, I., Sun, M., and Suer, G. A., Intelligent inventory management approaches for perishable pharmaceutical products in a healthcare supply chain, *Computers & Operations Research*, vol. 147, 105968, 2022.

Ala, A., Goli, A., Mirjalili, S., and Simic, V., A fuzzy multi-objective optimization model for sustainable healthcare supply chain network design, *Applied Soft Computing*, vol. 150, 111012, 2024.

Arampantzi, C., and Minis, I., A new model for designing sustainable supply chain networks and its application to a global manufacturer, *Journal of Cleaner Production*, vol. 156, pp. 276-292, 2017.

Ariningsih, P. K., et al., A multi-period pharmaceutical distribution network design considering supply frequency, equity, and waste, *Computers & Operations Research*, 2025.

Azad, N., Saharidis, G. K. D., Davoudpour, H., Malekly, H., and Yektamaram, S. A., Strategies for protecting supply chain networks against facility and transportation disruptions, *Annals of Operations Research*, vol. 210, pp. 125-163, 2013.

Bani, E. A., et al., Designing a sustainable reverse supply chain network for COVID-19 vaccine waste under uncertainty, *Computers & Industrial Engineering*, vol. 171, 108808, 2022.

Belien, J., and Force, H., Supply chain management of blood products: A literature review, *European Journal of Operational Research*, vol. 217, no. 1, pp. 1-16, 2012.

Choi, T. M., Innovative bring-service-near-your-home operations under Corona-Virus (COVID-19/SARS-CoV-2) outbreak: Can logistics become the messiah?, *Transportation Research Part E: Logistics and Transportation Review*, vol. 140, 101961, 2020.

Chopra, S., and Meindl, P., *Supply Chain Management: Strategy, Planning, and Operation*, 6th Edition, Pearson, Boston, 2016.

Chowdhury, N. R., et al., Modeling a sustainable vaccine supply chain for a developing economy, *Journal of Cleaner Production*, 2022.

Daskin, M. S., Coullard, C. R., and Shen, Z. J. M., An inventory-location model: Formulation, solution algorithm and computational results, *Annals of Operations Research*, vol. 110, pp. 83-106, 2002.

Diabat, A., and Simchi-Levi, D., A carbon-capped supply chain network problem, in *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management*, IEEE, pp. 523-527, 2009.

Elhedhli, S., and Merrick, R., Green supply chain network design to reduce carbon emissions, *Transportation Research Part D: Transport and Environment*, vol. 17, no. 5, pp. 370-379, 2012.

Fahimnia, B., Jabbarzadeh, A., Ghavamifar, A., and Bell, M., Supply chain design for efficient and effective blood supply in disasters, *International Journal of Production Economics*, vol. 183, pp. 700-709, 2017.

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E., van Nunen, J. A. E. E., and van Wassenhove, L. N., Quantitative models for reverse logistics: A review, *European Journal of Operational Research*, vol. 103, no. 1, pp. 1-17, 1997.

Gendron, B., and Semet, F., Formulations and relaxations for a multi-echelon capacitated location-distribution problem, *Computers & Operations Research*, vol. 36, no. 5, pp. 1335-1355, 2009.

Georgiadis, G. P., and Georgiadis, M. C., Optimal planning of the COVID-19 vaccine supply chain, *Vaccine*, vol. 39, no. 37, pp. 5302-5312, 2021.

Gilani, H., and Sahebi, H., A data-driven robust optimization model by cutting hyperplanes on vaccine access uncertainty in COVID-19 vaccine supply chain, *Omega*, vol. 110, 102637, 2022.

Golestani, M., Moosavirad, S. H., Asadi, Y., and Biglari, S., A multi-objective green hub location problem with multi item-multi temperature joint distribution for perishable products in cold supply chain, *Sustainable Production and Consumption*, vol. 27, pp. 1183-1194, 2021.

Goodarzian, F., Ghasemi, P., Gunasekaren, A., Taleizadeh, A. A., and Abraham, A., A sustainable-resilience healthcare network for handling COVID-19 pandemic, *Annals of Operations Research*, vol. 312, no. 2, pp. 761-825, 2022.

Goodarzian, F., Hoseini-Nasab, H., Toloo, M., and Fakhrzad, M. B., Designing a new medicine supply chain network considering production technology policy using two novel heuristic algorithms, *RAIRO - Operations Research*, vol. 55, no. 2, pp. 1015-1042, 2021b.

Goodarzian, F., Taleizadeh, A. A., Ghasemi, P., and Abraham, A., An integrated sustainable medical supply chain network during COVID-19, *Engineering Applications of Artificial Intelligence*, vol. 100, 104188, 2021a.

Goodarzian, F., and Ghasemi, P., A case-driven simulation-optimization model for sustainable medical logistics network, *Socio-Economic Planning Sciences*, vol. 101, 102271, 2025.

Goodarzian, F., et al., A new bi-objective green medicine supply chain network design under uncertainty, *Computers & Industrial Engineering*, vol. 160, 107535, 2021c.

Govindan, K., Fattahi, M., and Keyvanshokooh, E., Supply chain network design under uncertainty: A comprehensive review and future research directions, *European Journal of Operational Research*, vol. 263, no. 1, pp. 108-141, 2017.

Govindan, K., Mina, H., and Alavi, B., A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19), *Transportation Research Part E: Logistics and Transportation Review*, vol. 138, 101967, 2020.

Govindan, K., Soleimani, H., and Kannan, D., Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future, *European Journal of Operational Research*, vol. 240, no. 3, pp. 603-626, 2015.

Govindan, K., et al., A green reverse logistics network design for medical waste management: A circular economy transition through case approach, *Annals of Operations Research*, 2022.

Guo, Y., Yu, J., Allaoui, H., and Choudhary, A., Lateral collaboration with cost-sharing in sustainable supply chain optimisation: A combinatorial framework, *Transportation Research Part E: Logistics and Transportation Review*, vol. 157, 102593, 2022.

Hajipour Machiani, N., et al., Designing a new sustainable healthcare network considering the production and distribution of personal protective equipment, *Expert Systems with Applications*, vol. 262, 2025.

Hajipour, V., Fattahi, P., Tavana, M., and Di Caprio, D., Multi-objective multi-layer congested facility location-allocation problem optimization with Pareto-based meta-heuristics, *Applied Mathematical Modelling*, vol. 40, no. 7-8, pp. 4948-4969, 2016.

Halim, I., Ang, P., and Adhitya, A., A decision support framework and system for design of sustainable pharmaceutical supply chain network, *Clean Technologies and Environmental Policy*, vol. 21, pp. 431-446, 2019.

Hansen, K. R. N., and Grunow, M., Planning operations before market launch for balancing time-to-market and risks in pharmaceutical supply chains, *International Journal of Production Economics*, vol. 161, pp. 129-139, 2015.

Hosseinifard, Z., and Abbasi, B., The inventory centralization impacts on sustainability of the blood supply chain, *Computers & Operations Research*, vol. 89, pp. 206-212, 2018.

Hsieh, C. L., An evolutionary-based optimization for a multi-objective blood banking supply chain model, in *Modern Advances in Applied Intelligence (IEA/AIE)*, Springer, pp. 511-520, 2014.

Ivanov, D., Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case, *Transportation Research Part E: Logistics and Transportation Review*, vol. 136, 101922, 2020.

Jabbarzadeh, A., Fahimnia, B., and Seuring, S., Dynamic supply chain network design for the supply of blood in disasters: A robust model with real world application, *Transportation Research Part E: Logistics and Transportation Review*, vol. 70, pp. 225-244, 2014.

Jahani, H., Abbasi, B., Sheu, J.-B., and Klibi, W., Supply chain network design with financial considerations: A comprehensive review, *European Journal of Operational Research*, vol. 312, no. 3, pp. 799-839, 2024.

Kchaou Boujelben, M., Gicquel, C., and Minoux, M., A MILP model and heuristic approach for facility location under multiple operational constraints, *Computers & Industrial Engineering*, vol. 96, pp. 446-461, 2016.

Klose, A., and Drexl, A., Facility location models for distribution system design, *European Journal of Operational Research*, vol. 162, no. 1, pp. 4-29, 2005.

Kratica, J., Dugosija, D., and Savic, A., A new mixed integer linear programming model for the multi-level uncapacitated facility location problem, *Applied Mathematical Modelling*, vol. 38, no. 7-8, pp. 2118-2129, 2014.
Kumar, A., and Kumar, K., An uncertain sustainable supply chain network design for regulating greenhouse gas emission and supply chain cost, *Cleaner Logistics and Supply Chain*, vol. 10, 100142, 2024.
Kumar, R., Ganapathy, L., Gokhale, R., and Tiwari, M. K., Quantitative approaches for the integration of production and distribution planning in the supply chain: a systematic literature review, *International Journal of Production Research*, vol. 58, no. 11, pp. 3527-3553, 2020.
Melo, M. T., Nickel, S., and Saldanha-da-Gama, F., Facility location and supply chain management - A review, *European Journal of Operational Research*, vol. 196, no. 2, pp. 401-412, 2009.
Meneses, M., Santos, D., and Barbosa-Povoa, A., Modelling the blood supply chain, *European Journal of Operational Research*, vol. 307, no. 2, pp. 499-518, 2023.
Mete, H. O., and Zabinsky, Z. B., Stochastic optimization of medical supply location and distribution in disaster management, *International Journal of Production Economics*, vol. 126, no. 1, pp. 76-84, 2010.
Nahmias, S., Perishable inventory theory: A review, *Operations Research*, vol. 30, no. 4, pp. 680-708, 1982.
Nayeri, S., Asadi-Gangraj, E., and Emami, S., Goal programming-based post-disaster decision making for allocation and scheduling the rescue units in natural disaster with time-window, *International Journal of Industrial Engineering & Production Research*, vol. 29, no. 1, pp. 65-78, 2018.
Nosrati-Abarghooee, S., et al., Designing reverse logistics network for healthcare waste management considering epidemic disease conditions, *Applied Soft Computing*, vol. 142, 110372, 2023.
Or, I., and Pierskalla, W. P., A transportation location-allocation model for regional blood banking, *AIIE Transactions*, vol. 11, no. 2, pp. 86-95, 1979.
Osorio, A. F., Brailsford, S. C., and Smith, H. K., A structured review of quantitative models in the blood supply chain, *International Journal of Production Research*, vol. 53, no. 24, pp. 7191-7212, 2015.
Peng, P., Snyder, L. V., Lim, A., and Liu, Z., Reliable logistics networks design with facility disruptions, *Transportation Research Part B: Methodological*, vol. 45, no. 8, pp. 1190-1211, 2011.
Pierskalla, W. P., Supply chain management of blood banks, in *Operations Research and Health Care*, Springer, Boston, pp. 103-145, 2005.
Queiroz, M. M., Ivanov, D., Dolgui, A., and Wamba, S. F., Impacts of epidemic outbreaks on supply chains: mapping a research agenda amid the COVID-19 pandemic through a structured literature review, *Annals of Operations Research*, vol. 319, pp. 1159-1196, 2022.
Rawls, C. G., and Turnquist, M. A., Pre-positioning planning for emergency response with service quality constraints, *OR Spectrum*, vol. 33, no. 3, pp. 481-498, 2011.
Rekabi, S., et al., Designing a responsive-sustainable-resilient blood supply chain network considering uncertainty and disruption, *Expert Systems with Applications*, vol. 238, 2024.
Remko, V. H., Research opportunities for a more resilient post-COVID-19 supply chain: closing the gap between research findings and industry practice, *International Journal of Operations & Production Management*, vol. 40, no. 4, pp. 341-355, 2020.
Rezaei, S., and Kheirkhah, A., A comprehensive approach in designing a sustainable closed-loop supply chain network using cross-docking operations, *Computational and Mathematical Organization Theory*, vol. 24, pp. 51-98, 2018.
Rottkemper, B., Fischer, K., Blecken, A., and Danne, C., Inventory relocation for overlapping disaster settings in humanitarian operations, *OR Spectrum*, vol. 33, no. 3, pp. 721-749, 2011.
Sabouhi, F., Jabalameli, M. S., and Jabbarzadeh, A., An optimization approach for sustainable and resilient supply chain design with regional considerations, *Computers & Industrial Engineering*, vol. 159, 107510, 2021.
Saedi, S., Kundakcioglu, O. E., and Henry, A. C., Mitigating the impact of drug shortages for a healthcare facility: An inventory management approach, *European Journal of Operational Research*, vol. 251, no. 1, pp. 107-123, 2016.
Sahin, G., Sural, H., and Meral, S., Locational analysis for regionalization of Turkish Red Crescent blood services, *Computers & Operations Research*, vol. 34, no. 3, pp. 692-704, 2007.
Savadkoohi, E., Mousazadeh, M., and Torabi, S. A., A possibilistic location-inventory model for multi-period perishable pharmaceutical supply chain network design, *Chemical Engineering Research and Design*, vol. 138, pp. 490-505, 2018.
Sazvar, Z., et al., Designing a sustainable closed-loop pharmaceutical supply chain in a competitive market considering demand uncertainty, manufacturer's brand and waste management, *Annals of Operations Research*, 2021.

Seuring, S., and Muller, M., From a literature review to a conceptual framework for sustainable supply chain management, *Journal of Cleaner Production*, vol. 16, no. 15, pp. 1699-1710, 2008.
Shen, Z. J. M., Coullard, C., and Daskin, M. S., A joint location-inventory model, *Transportation Science*, vol. 37, no. 1, pp. 40-55, 2003.
Snyder, L. V., Facility location under uncertainty: a review, *IIE Transactions*, vol. 38, no. 7, pp. 547-564, 2006.
Sohrabi, M., Zandieh, M., and Afshar-Nadjafi, B., A simple empirical inventory model for managing the processed corneal tissue equitably in hospitals with demand differentiation, *Computational and Applied Mathematics*, vol. 40, no. 8, 2021.
Spieske, A., and Birkel, H., Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic, *Computers & Industrial Engineering*, vol. 158, 107452, 2021.
Tao, W., et al., Optimisation model of SPD supply chain for medical consumables based on mixed integer programming, *Promet - Traffic & Transportation*, vol. 37, no. 2, 2025.
Tat, R., Heydari, J., and Rabbani, M., A mathematical model for pharmaceutical supply chain coordination: Reselling medicines in an alternative market, *Journal of Cleaner Production*, vol. 268, 121897, 2020.
Tirkolaee, E. B., Abbasian, P., and Weber, G. W., Sustainable fuzzy multi-trip location-routing problem for medical waste management during the COVID-19 outbreak, *Science of the Total Environment*, vol. 756, 143607, 2021.
Vali-Siar, M. M., and Roghanian, E., Sustainable, resilient and responsive mixed supply chain network design under hybrid uncertainty with considering COVID-19 pandemic disruption, *Sustainable Production and Consumption*, vol. 30, pp. 278-300, 2022.
Wang, H. F., and Hsu, H. W., A closed-loop logistic model with a spanning-tree based genetic algorithm, *Computers & Operations Research*, vol. 37, no. 2, pp. 376-389, 2010.
Wolsey, L. A., *Integer Programming*, 2nd Edition, John Wiley & Sons, Hoboken, 2020.
Xu, Y., and Szmerekovsky, J., The impact of transshipment on an integrated platelet supply chain: A multi-stage stochastic programming approach, *Computers & Industrial Engineering*, vol. 176, 108991, 2023.
Yang, Y., Yin, Y., Wang, D., Ignatius, J., Cheng, T., and Dhamotharan, L., Distributionally robust multi-period location-allocation with multiple resources and capacity levels in humanitarian logistics, *European Journal of Operational Research*, vol. 305, no. 3, pp. 1042-1062, 2023.
Zandkarimkhani, S., Mina, H., Biuki, N., and Govindan, K., A chance constrained fuzzy goal programming approach for perishable pharmaceutical supply chain network design, *Annals of Operations Research*, vol. 295, pp. 425-452, 2020.
Zhang, T., Xie, W., Wei, M., and Xie, X., Multi-objective sustainable supply chain network optimization based on chaotic particle-ant colony algorithm, *PLoS ONE*, vol. 18, no. 7, e0278814, 2023.
Zwaida, T. A., Pham, C., and Beauregard, Y., Optimization of inventory management to prevent drug shortages in the hospital supply chain, *Applied Sciences*, vol. 11, no. 6, 2726, 2021.

Acknowledgments:

The authors extend their appreciation to the Deanship of Graduate Studies and Scientific Research at Jazan University for funding this research work through the project number 'JU-RSP2026'.

Funding

The authors extend their appreciation to the Deanship of Graduate Studies and Scientific Research at Jazan University for funding this research work through the project number 'JU-RSP2026'.

Ethics declaration

Not applicable.

Author contributions

All authors of this paper, contributed significantly to the conception, design, execution, and interpretation of the study.

Data availability
The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Consent to Publish declaration
Consent to Publish declaration: not applicable.

Consent to Participate declaration
Consent to Participate declaration: not applicable.