



A Multi-Objective Decision Framework for Integrated Transport and Warehouse Capacity Allocation under Operational and Environmental Constraints

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Abstract

The increasing complexity of logistics networks requires simultaneous consideration of transportation capacity, warehouse capacity, operational efficiency, and environmental sustainability. Conventional logistics planning approaches frequently optimize transportation and warehousing decisions independently, which can result in capacity imbalance, unnecessary transportation movements, warehouse congestion, and increased carbon emissions. This study proposes a multi-objective decision framework for integrated transport and warehouse capacity allocation under operational and environmental constraints. The proposed framework jointly determines transportation capacity allocation, warehouse utilization, shipment assignment, inventory flow, and vehicle movement while considering transportation cost, warehouse operating cost, capacity utilization, delivery requirements, and carbon emissions. A multi-objective mixed-integer optimization model is formulated to minimize total logistics cost and environmental impact while maximizing capacity utilization and maintaining required service levels. Operational constraints include vehicle capacity, warehouse storage limits, shipment demand, delivery requirements, inventory balance, transportation availability, and warehouse handling capacity. Environmental constraints incorporate vehicle-related emissions and warehouse energy consumption. The model generates a set of Pareto-optimal solutions representing different trade-offs between economic efficiency, operational performance, and environmental sustainability. A scenario-based evaluation is proposed to examine the effects of demand variation, transportation capacity limitations, warehouse capacity constraints, and emission restrictions. The framework provides an integrated decision-support mechanism for logistics managers to allocate limited transport and warehouse resources while maintaining service requirements and controlling environmental impacts.

Keywords: Multi-objective optimization, transportation capacity, warehouse capacity, logistics allocation, sustainable logistics, carbon emissions, supply chain optimization

1. Introduction

Modern logistics systems depend on the coordinated utilization of transportation networks and warehouse facilities. Increasing customer demand, shorter delivery windows, fragmented shipments, and sustainability requirements have made capacity planning a critical decision problem for logistics organizations. Transportation capacity determines the ability to move goods between supply and demand locations, whereas warehouse capacity determines the ability to receive, store, process, and dispatch products. When these capacities are planned independently, imbalances may occur between available storage space and transportation resources, resulting in warehouse congestion, underutilized vehicles, additional trips, delayed deliveries, and increased operating costs.

The integration of economic and environmental objectives has become increasingly important in logistics planning.

Recent research has demonstrated the value of multi-objective optimization for simultaneously considering logistics costs and environmental performance. Xie *et al.* developed an integrated multi-objective model connecting energy, inventory, and transportation decisions and demonstrated the importance of jointly planning capacity and daily operations. Similarly, recent sustainable supply-chain models have incorporated cost, emissions, reliability, facility capacity, and transportation decisions within integrated optimization frameworks.

Warehouse operations also contribute substantially to logistics performance through storage utilization, material handling, energy consumption, and internal transportation. Recent research has investigated multi-objective simulation-optimization for warehouse systems by explicitly considering energy consumption and operational travel time. At the distribution level, integrated location and routing

models demonstrate that warehouse decisions and transportation decisions can significantly influence one another.

Despite these developments, transportation capacity and warehouse capacity are frequently addressed as separate planning problems. Such separation can produce locally efficient decisions that are inefficient at the network level. For example, allocating additional vehicles without sufficient warehouse processing capacity may increase congestion, while increasing warehouse capacity without corresponding transportation availability may create unused storage resources. Therefore, an integrated decision framework is required to coordinate both types of capacity.

This study proposes a multi-objective decision framework that jointly allocates transportation and warehouse capacity while considering operational and environmental constraints. The framework minimizes logistics cost and carbon emissions while improving capacity utilization and maintaining service requirements. The proposed model incorporates vehicle capacity, warehouse storage capacity, inventory balance, shipment assignment, transportation availability, warehouse handling capacity, and environmental restrictions.

The main contributions of the study are the development of an integrated transport–warehouse capacity allocation model, formulation of multiple economic, operational, and environmental objectives, incorporation of capacity and service constraints, generation of Pareto-optimal allocation alternatives, and scenario-based analysis of demand, capacity, and environmental conditions.

2. Literature Review

2.1 Multi-Objective Logistics Optimization

Multi-objective optimization has become an important approach for logistics planning because logistics decisions generally involve competing objectives such as transportation cost, resource utilization, service performance, and environmental sustainability. Recent vehicle-routing research has demonstrated the use of advanced optimization techniques to simultaneously handle capacity and time-window constraints ^[1]. Dynamic vehicle-routing studies have further shown that changing operational conditions require adaptive decision-making and flexible allocation of transportation resources ^[2]. Forecast reconciliation and hierarchical forecasting approaches have also become relevant to logistics planning because decisions at different geographical and operational levels need to remain consistent ^[3].

2.2 Transportation Capacity Allocation

Transportation capacity allocation involves assigning available vehicles or transport resources to shipment requirements while satisfying vehicle capacity, delivery schedules, and operational restrictions. Robust optimization has increasingly been used where transportation demand is uncertain. Xiang *et al.* ^[4] investigated fleet deployment and empty-container repositioning under demand uncertainty and demonstrated the importance of coordinating capacity decisions with uncertain demand. Freight-demand and freight-rate forecasting using econometric and artificial-intelligence methods has also demonstrated the potential of predictive techniques for supporting transportation planning

^[5]. These studies indicate that effective transportation allocation requires both accurate demand information and optimization mechanisms capable of responding to capacity limitations.

2.3 Warehouse Capacity and Storage Allocation

Warehouse capacity represents a critical resource because storage availability and handling capability directly influence the movement and availability of goods throughout the supply chain. Recent studies on warehouse and logistics systems have emphasized the need to optimize storage, material movement, and resource utilization simultaneously. Research on multimodal transport systems has highlighted the importance of coordinating infrastructure and logistics resources across interconnected transportation networks ^[6]. Similarly, studies of national and regional logistics capacity have emphasized the role of infrastructure availability and logistics-resource allocation in improving overall transportation performance ^[7]. However, these studies primarily focus on transportation infrastructure or network-level logistics development rather than jointly allocating warehouse and transportation capacity.

2.4 Integrated Transportation and Warehouse Planning

Transportation and warehouse decisions are highly interdependent. Transportation capacity determines the quantity of goods that can enter or leave a warehouse, whereas warehouse storage and handling capacity determine the amount of freight that can be processed within a particular period. Recent research on forecasting and optimization in road freight transportation emphasizes the need to connect predictive information with downstream operational decisions rather than treating forecasting and optimization as independent processes ^[8]. Similarly, learning-based robust optimization has been applied to freight transportation under uncertainty, demonstrating the potential benefits of integrating predictive models with optimization decisions ^[9].

Capacitated vehicle-routing research has further examined the interaction between transportation resources, demand distribution, and operational constraints ^[10]. Research on cargo pickup and delivery under uncertainty has also emphasized the importance of incorporating uncertainty into logistics decision-support systems ^[11]. These developments provide a basis for extending integrated optimization from vehicle routing toward coordinated transportation and warehouse capacity allocation.

2.5 Environmental Sustainability in Logistics

Environmental sustainability has become an increasingly important component of logistics optimization. Transportation operations generate emissions through fuel consumption, vehicle distance, congestion, and empty movements, while warehouses contribute through electricity consumption, material handling, and equipment operation. Recent vehicle-routing research has incorporated environmental considerations together with transportation efficiency and operational constraints ^[12]. Digital-twin-based logistics research has additionally emphasized the importance of monitoring operational risks and resource conditions across complex logistics networks ^[13]. Such

approaches demonstrate the increasing need to incorporate environmental and operational factors within integrated decision-making frameworks.

2.6 Capacity Utilization and Dynamic Logistics Decisions

Efficient utilization of available capacity is essential for controlling logistics costs and reducing unnecessary resource consumption. Agent-based simulation has recently been applied to analyze multimodal transportation flows and the interactions among logistics resources [14]. Dynamic empty-vehicle repositioning research has further demonstrated the relevance of rolling-horizon decisions for reducing inefficient vehicle movements when transportation conditions and time requirements change [15]. These findings suggest that static capacity allocation may be insufficient when demand, transportation availability, warehouse occupancy, and environmental conditions vary over time.

2.7 Research Gap

The existing literature demonstrates significant progress in multi-objective logistics optimization, transportation capacity planning, warehouse management, sustainable logistics, and uncertainty-aware decision-making. However, several research gaps remain. First, transportation and warehouse capacity are often optimized independently, despite their strong operational interdependence. Second, many transportation models focus primarily on routing and vehicle capacity without explicitly incorporating warehouse storage and handling capacity. Third, environmental objectives are frequently considered separately from operational capacity allocation. Fourth, uncertainty in demand and resource availability can reduce the effectiveness of static allocation strategies.

Therefore, the proposed study develops an integrated multi-objective decision framework that jointly allocates transportation capacity and warehouse capacity while considering operating cost, capacity utilization, service requirements, and environmental constraints. The framework combines these objectives within a unified optimization model and generates alternative Pareto-optimal solutions, allowing decision-makers to examine the trade-offs between economic efficiency, operational performance, and environmental sustainability.

3. Research Methodology

The proposed methodology develops an integrated decision framework for allocating transportation and warehouse capacity while simultaneously considering operational efficiency, logistics cost, service requirements, and environmental sustainability. The framework consists of data collection and preprocessing, capacity estimation, demand and resource analysis, multi-objective optimization, Pareto-solution generation, and performance evaluation.

3.1 Data Collection

The proposed framework requires transportation, warehouse, shipment, operational, and environmental data. Transportation-related variables include vehicle type, vehicle capacity, availability, travel distance, travel time, fuel consumption, transportation cost, and emission factor. Warehouse-related variables include total storage capacity, occupied capacity, handling capacity, operating cost, energy

consumption, and warehouse location. Shipment-level information includes origin, destination, product quantity, required delivery period, warehouse assignment, and service requirements.

Historical shipment and operational records can be used to determine demand patterns and resource utilization. Environmental information, such as vehicle emission factors and warehouse energy consumption, is incorporated to quantify the environmental impact associated with different allocation decisions.

3.2 Data Preprocessing

The collected data are examined for missing values, duplicate observations, inconsistent units, and abnormal records. Missing numerical values can be handled using appropriate statistical or interpolation techniques, while categorical variables such as vehicle type, warehouse category, and product class are transformed into machine-readable representations. Transportation distances, operating costs, capacity values, and emission measurements are standardized to ensure consistency across the dataset.

The data are subsequently aggregated according to the selected planning horizon, such as daily or weekly periods. Transportation and warehouse utilization rates are calculated to establish the available and occupied capacity for each planning period.

3.3 Transportation Capacity Estimation

Transportation capacity is determined based on the available vehicles and their corresponding carrying capacities. The available transportation capacity during period t is represented as:

$$TC_t = \sum_{v=1}^V Cap_v A_{v,t}$$

where TC_t represents total available transportation capacity, Cap_v represents the capacity of vehicle v , and $A_{v,t}$ is a binary availability variable indicating whether vehicle v is available during period t .

The formulation can additionally incorporate vehicle type, operating schedule, maintenance requirements, and delivery restrictions to prevent allocation of unavailable transportation resources.

3.4 Warehouse Capacity Estimation

Warehouse capacity is evaluated using both storage and handling limitations. The remaining storage capacity of warehouse w during period t is calculated as:

$$WC_{w,t} = Cap_w - I_{w,t}$$

where Cap_w represents the total storage capacity and $I_{w,t}$ represents the occupied inventory capacity.

Warehouse handling capacity is represented separately because a warehouse may have sufficient physical storage space but insufficient processing capability. Therefore,

$$In_{w,t} + Out_{w,t} \leq HC_w$$

where $In_{w,t}$ and $Out_{w,t}$ represent inbound and outbound quantities, respectively, and HC_w represents the maximum handling capacity.

3.5 Integrated Capacity Allocation

The central component of the proposed methodology is the joint allocation of transportation and warehouse capacity. Instead of determining vehicle assignments and warehouse utilization independently, the model evaluates their interaction within a common decision framework.

The shipment assignment variable is defined as

$$x_{vwijt} = \begin{cases} 1, & \text{if vehicle } v \text{ transports shipment } i \text{ through warehouse } w \\ 0, & \text{otherwise} \end{cases}$$

This decision variable connects transportation resources with warehouse operations and allows the optimization model to determine feasible combinations of vehicle and warehouse assignments.

3.6 Multi-Objective Optimization

The proposed model simultaneously considers four major objectives: transportation cost, warehouse operating cost, environmental impact, and capacity utilization.

The transportation-cost objective is expressed as

$$\min Z_1 = \sum_{v,w,i,j,t} C_{vij} x_{vwijt}$$

The warehouse-cost objective is

$$\min Z_2 = \sum_{w,t} C_w^W I_{w,t}$$

The environmental objective considers both transportation and warehouse emissions

$$\min Z_3 = \sum_{v,i,j,t} E_{vij}^T x_{vwijt} + \sum_{w,t} E_{w,t}^W$$

Capacity utilization is incorporated as a maximization objective

$$\max Z_4 = \frac{\text{Used Transportation Capacity} + \text{Used Warehouse Capacity}}{\text{Available Transportation Capacity} + \text{Available Warehouse Capacity}}$$

These objectives represent conflicting requirements. For example, minimizing transportation cost may increase vehicle utilization but may also increase emissions, whereas minimizing emissions may require additional consolidation or alternative transportation resources.

3.7 Operational Constraints

The optimization model is subject to transportation capacity, warehouse storage, warehouse handling, demand fulfillment, vehicle availability, inventory balance, and service-level constraints.

Transportation capacity is constrained by

$$\sum_{i,j,w} Q_{ij,t} x_{vwijt} \leq Cap_v$$

Warehouse storage is constrained by

$$I_{w,t} \leq Cap_w$$

Demand fulfillment is represented as

$$\sum_{v,w} Q_{ij,t} x_{vwijt} \geq D_{ij,t}$$

Inventory balance is maintained using

$$I_{w,t} = I_{w,t-1} + In_{w,t} - Out_{w,t}$$

These constraints ensure that the resulting allocation remains operationally feasible.

3.8 Environmental Constraint

In addition to minimizing environmental impact as an objective, an emission limit can be incorporated into the model:

$$E_t^T + E_t^W \leq E^{max}$$

where E_t^T represents transportation emissions, E_t^W represents warehouse emissions, and E^{max} represents the maximum allowable emissions during the planning period. This constraint enables the framework to evaluate logistics allocation under different environmental regulations or organizational sustainability targets.

3.9 Pareto-Based Decision Framework

Because the objectives may conflict, a single optimal solution may not adequately represent the available decision alternatives. Therefore, the proposed framework generates a set of Pareto-optimal solutions. Each solution represents a different trade-off between cost, capacity utilization, service performance, and environmental impact.

The resulting Pareto frontier enables logistics decision-makers to select an allocation according to their operational priorities without requiring the optimization model to impose a single predetermined preference among the objectives.

4. Mathematical Model

The proposed mathematical model formulates the integrated allocation of transportation and warehouse capacity as a multi-objective optimization problem. The model simultaneously considers transportation cost, warehouse operating cost, environmental emissions, and capacity utilization while satisfying shipment demand, vehicle availability, warehouse storage, handling capacity, and service-level requirements.

4.1 Sets and Parameters

Let V represent the set of available vehicles, W the set of warehouses, N the set of logistics locations, and T the set of planning periods.

The principal parameters are defined as follows

Cap_v — capacity of vehicle v .

Cap_w — storage capacity of warehouse w .

HC_w — handling capacity of warehouse w .

$D_{ij,t}$ — shipment demand from location i to location j during period t .

C_{vij} — transportation cost associated with vehicle v travelling from i to j .

C_w^W — operating cost of warehouse w .

E_{vij}^T — transportation emissions associated with vehicle v .

$E_{w,t}^W$ — warehouse emissions during period t .

$A_{v,t}$ — availability of vehicle v during period t .

E^{max} — maximum permitted emissions.

SL^{min} — minimum required service level.

4.2 Decision Variables

The principal shipment-allocation variable is defined as:

$$x_{vwijt} = \begin{cases} 1, & \text{if vehicle } v \text{ transports shipment from } i \text{ to } j \\ & \text{through warehouse } w \text{ during period } t, \\ 0, & \text{otherwise.} \end{cases}$$

The inventory variable is

$I_{w,t}$ = inventory quantity stored at warehouse w during period t .

The unmet-demand variable is

$U_{ij,t}$ = unfulfilled demand between i and j during period t .

These variables allow the model to simultaneously determine transportation assignments, warehouse utilization, and demand fulfillment.

4.3 Transportation Cost Objective

The first objective minimizes the total transportation cost:

$$\min Z_1 = \sum_{v \in V} \sum_{w \in W} \sum_{i,j \in N} \sum_{t \in T} C_{vij} x_{vwijt}$$

This objective encourages the allocation of shipments to transportation resources that provide the required capacity at lower operating cost.

4.4 Warehouse Operating Cost Objective

The second objective minimizes warehouse operating expenditure:

$$\min Z_2 = \sum_{w \in W} \sum_{t \in T} C_w^W I_{w,t}$$

This objective discourages unnecessary concentration of inventory in high-cost warehouse facilities.

4.5 Environmental Objective

Transportation and warehouse activities jointly contribute to environmental impact. Therefore, total emissions are minimized using:

$$\min Z_3 = \sum_{v,w,i,j,t} E_{vij}^T x_{vwijt} + \sum_{w,t} E_{w,t}^W$$

The first term represents transportation-related emissions, while the second represents warehouse-related emissions.

4.6 Capacity Utilization Objective

The fourth objective maximizes the utilization of available transportation and warehouse resources:

$$\max Z_4 = \frac{\sum_{v,w,i,j,t} Q_{ij,t} x_{vwijt} + \sum_{w,t} I_{w,t}}{\sum_{v,t} Cap_v A_{v,t} + \sum_{w,t} Cap_w}$$

Higher utilization indicates that available logistics resources are being used more effectively without violating capacity constraints.

4.7 Integrated Multi-Objective Function

The four objectives can be converted into a single weighted formulation:

$$\min Z = \alpha Z_1 + \beta Z_2 + \gamma Z_3 - \delta Z_4$$

where α , β , γ , and δ represent decision-maker-defined weights for transportation cost, warehouse cost, environmental impact, and capacity utilization, respectively. The negative sign associated with Z_4 converts the maximization objective into the minimization framework. Alternatively, the model can be solved directly using a Pareto-based multi-objective optimization algorithm without assigning fixed weights.

4.8 Transportation Capacity Constraint

The quantity assigned to each vehicle cannot exceed its available carrying capacity:

$$\sum_{w,i,j} Q_{ij,t} x_{vwijt} \leq Cap_v A_{v,t} \quad \forall v, t$$

This constraint prevents overloading and ensures that unavailable vehicles are not assigned shipments.

4.9 Warehouse Storage Constraint

The inventory stored in each warehouse cannot exceed its physical capacity:

$$I_{w,t} \leq Cap_w \quad \forall w, t$$

This constraint prevents warehouse over-utilization.

4.10 Warehouse Handling Constraint

The total inbound and outbound flow through a warehouse must remain within its handling capability:

$$In_{w,t} + Out_{w,t} \leq HC_w \quad \forall w, t$$

This constraint accounts for operational limitations even when sufficient physical storage space is available.

4.11 Demand Fulfillment Constraint

The model must satisfy shipment demand whenever sufficient resources are available:

$$\sum_{v,w} Q_{ij,t} x_{vwijt} + U_{ij,t} \geq D_{ij,t} \quad \forall i, j, t$$

The variable $U_{ij,t}$ allows the model to represent unmet demand when capacity limitations make complete fulfillment impossible.

4.12 Inventory Balance Constraint

Warehouse inventory is maintained through the following balance equation:

$$I_{w,t} = I_{w,t-1} + In_{w,t} - Out_{w,t} \quad \forall w, t$$

This ensures consistency between incoming shipments, outgoing shipments, and warehouse inventory.

4.13 Environmental Constraint

The total emissions generated by transportation and warehouse operations are restricted by:

$$\sum_{v,w,i,j,t} E_{vij}^T x_{vwijt} + \sum_{w,t} E_{w,t}^W \leq E^{max}$$

This constraint enables the proposed framework to operate within a predefined organizational or regulatory environmental target.

4.14 Service-Level Constraint

The allocation must maintain a minimum service level:

$$\frac{\sum_{i,j,t} (D_{ij,t} - U_{ij,t})}{\sum_{i,j,t} D_{ij,t}} \geq SL^{min}$$

This prevents the optimization process from achieving low cost or emissions by excessively sacrificing customer demand fulfillment.

4.15 Non-Negativity and Binary Constraints

The decision variables satisfy:

$$x_{vwijt} \in \{0, 1\}$$

And

$$I_{w,t} \geq 0, U_{ij,t} \geq 0$$

The resulting formulation represents a multi-objective mixed-integer optimization problem in which transportation and warehouse capacities are jointly allocated under operational and environmental constraints. The model can subsequently be solved using Pareto-based evolutionary optimization, weighted-sum optimization, or another suitable multi-objective optimization technique.

5. Solution Approach and Experimental Design

The proposed mathematical model is solved using a multi-objective optimization strategy to identify feasible capacity-allocation solutions under competing economic, operational, and environmental objectives. The experimental design evaluates whether integrated transportation–warehouse allocation can improve resource utilization while maintaining service requirements and controlling environmental impact.

5.1 Optimization Strategy

The multi-objective model can be solved using a Pareto-based optimization approach. Instead of producing a single solution, the optimization process generates a set of non-dominated solutions. A solution is considered non-dominated when no other feasible solution simultaneously provides lower cost, lower emissions, and higher capacity utilization.

For larger logistics networks, evolutionary multi-objective algorithms such as NSGA-II can be employed because of their ability to handle mixed decision variables and conflicting objectives. For smaller instances, a weighted-sum mixed-integer optimization approach can be used to obtain benchmark solutions.

5.2 Experimental Dataset

The experimental dataset should contain synchronized transportation, warehouse, and shipment records. Each shipment record includes origin, destination, quantity, required delivery period, and assigned warehouse. Vehicle records include vehicle capacity, operating cost, availability, distance, fuel consumption, and emission factor. Warehouse records contain storage capacity, handling capacity, operating cost, occupancy, and energy consumption.

The dataset can be organized according to daily or weekly planning periods. Demand and capacity observations are aggregated for each period to determine the relationship between available logistics resources and shipment requirements.

5.3 Experimental Scenarios

Different operating scenarios are considered to evaluate the robustness of the proposed framework. The normal-capacity scenario represents regular demand and available

transportation and warehouse resources. The high-demand scenario increases shipment requirements while maintaining relatively fixed capacity. The transport-capacity reduction scenario evaluates the effect of vehicle shortages or temporary vehicle unavailability. The warehouse-capacity reduction scenario represents situations involving warehouse congestion or temporary facility restrictions. An environmental-restriction scenario can also be introduced by reducing the allowable emission threshold E^{max} . This scenario evaluates how the allocation changes when environmental requirements become more restrictive.

5.4 Baseline Models

The proposed integrated model can be compared with alternative allocation strategies. The first baseline independently allocates transportation and warehouse capacity without considering their interaction. The second baseline minimizes total logistics cost without explicitly optimizing environmental impact. The third baseline incorporates transportation cost and emissions but does not explicitly maximize joint capacity utilization. The proposed model simultaneously considers transportation cost, warehouse cost, emissions, capacity utilization, and service-level requirements.

This comparison allows the effect of integrated multi-objective planning to be evaluated against conventional independent allocation approaches.

5.5 Performance Evaluation Metrics

The performance of the proposed framework is evaluated using economic, operational, environmental, and capacity-related measures.

Transportation cost is calculated as the total cost incurred by vehicle movements, while warehouse cost represents storage and handling expenditure. Total logistics cost combines these components.

Transportation capacity utilization is calculated as

$$TCU = \frac{\text{Used Transportation Capacity}}{\text{Available Transportation Capacity}} \times 100$$

Warehouse utilization is calculated as

$$WCU = \frac{\text{Occupied Warehouse Capacity}}{\text{Total Warehouse Capacity}} \times 100$$

The overall environmental impact is measured through total transportation and warehouse emissions:

$$TE = TE_T + TE_W$$

where TE_T represents transportation emissions and TE_W represents warehouse emissions.

Service performance is measured using

$$SL = \frac{\text{Demand Fulfilled Within Required Time}}{\text{Total Demand}} \times 100$$

These metrics provide a comprehensive assessment of whether the proposed model improves logistics performance without achieving cost reductions at the expense of service or environmental requirements.

5.6 Sensitivity Analysis

Sensitivity analysis is conducted to determine how changes in key parameters influence the optimal allocation. Transportation capacity, warehouse capacity, shipment demand, emission limits, operating costs, and service-level requirements are systematically varied. For example, increasing demand can reveal the point at which available transportation or warehouse capacity becomes insufficient. Similarly, reducing warehouse capacity can demonstrate how the optimization model reallocates shipments among alternative facilities and transportation resources. Changes in the emission threshold can reveal the trade-off between environmental performance and logistics cost.

5.7 Pareto Solution Analysis

The resulting solutions are represented using a Pareto frontier. Each point on the frontier represents a feasible allocation with a specific combination of logistics cost, emissions, and capacity utilization. A reduction in emissions may require additional transportation or warehouse expenditure, whereas aggressive cost minimization may produce higher emissions.

The Pareto frontier therefore provides a decision-support mechanism for selecting an allocation according to the operational requirements of the logistics network rather than imposing a single fixed objective.

5.8 Statistical and Robustness Analysis

Multiple experimental runs can be performed for stochastic or evolutionary optimization approaches. Mean objective values, standard deviations, convergence behavior, and computational time can be reported. Scenario-based analysis can further determine whether the proposed framework maintains acceptable service and capacity utilization under changing demand and resource conditions.

The experimental design therefore provides a structured basis for evaluating the proposed integrated transportation–warehouse capacity allocation framework across economic, operational, environmental, and uncertain operating conditions.

6. Results and Discussion

The results section should evaluate the proposed integrated framework from four perspectives: economic performance, capacity utilization, environmental impact, and service-level performance. Since an actual transportation–warehouse dataset has not been provided, the numerical values below should be treated as illustrative/simulated values, not empirical findings. They can be replaced with actual experimental results when the model is implemented on a real dataset.

6.1 Comparison of Capacity Allocation Strategies

The proposed integrated multi-objective framework can be compared with independent transportation–warehouse allocation, cost-only optimization, and cost–emission optimization.

Table 1: Comparison of Capacity Allocation Strategies

Allocation Strategy	Total Logistics Cost	Transportation Utilization (%)	Warehouse Utilization (%)	Emissions	Service Level (%)
Independent Allocation	100.0	68.4	71.2	100.0	91.8
Cost-Minimization	94.6	76.3	78.5	108.7	93.1
Cost-Emission Optimization	98.2	73.8	81.6	91.4	94.7
Proposed Multi-Objective Framework	96.1	82.5	85.3	86.8	97.2

The illustrative results indicate that independent allocation produces relatively low resource coordination because transportation and warehouse decisions are optimized separately. The proposed framework achieves higher transportation and warehouse utilization while maintaining a higher service level. Although the cost is slightly higher than the cost-only strategy, the proposed approach provides improved environmental performance and service reliability.

6.2 Transportation and Warehouse Capacity Utilization

The proposed framework improves the coordination between available transportation and warehouse resources. Under independent allocation, approximately 68.4% of available transportation capacity and 71.2% of warehouse capacity are utilized. The proposed approach increases these values to approximately 82.5% and 85.3%, respectively. This improvement results from jointly considering vehicle availability, shipment demand, warehouse storage, and handling capacity. Instead of assigning transportation resources without considering downstream warehouse conditions, the proposed model selects allocations that maintain greater synchronization between inbound transportation flows and warehouse availability.

6.3 Environmental Performance

Environmental performance represents an important difference between the proposed framework and conventional cost-focused allocation. The illustrative results show that the proposed model reduces total emissions to 86.8% of the reference level, compared with 91.4% under the cost-emission model and 100% under independent allocation.

The reduction can be attributed to improved consolidation of shipments, more effective vehicle utilization, and better

coordination between transportation movements and warehouse operations. However, the environmental objective should not be interpreted independently from cost and service performance because aggressive emission minimization may increase transportation or warehouse expenditure.

6.4 Service-Level Performance

The proposed framework achieves an illustrative service level of 97.2%, compared with 91.8% for independent allocation. The improvement results from explicitly incorporating demand fulfillment and service-level constraints into the optimization model.

The service constraint prevents the optimization process from achieving lower cost or emissions by excessively delaying or rejecting shipments. Therefore, the proposed framework maintains a balance between operational efficiency and customer-service requirements.

6.5 Pareto-Frontier Analysis

The multi-objective formulation generates several non-dominated solutions rather than a single solution. The solutions represent different trade-offs between logistics cost and environmental impact. A solution with minimum cost may generate relatively higher emissions, whereas a solution with minimum emissions may require additional logistics expenditure.

The Pareto frontier allows decision-makers to select an allocation based on the desired balance between economic and environmental performance. This is particularly useful when logistics organizations operate under different sustainability targets or budget limitations.

6.6 Scenario Analysis: The framework can further be evaluated under different capacity and demand conditions.

Table 2: The scenario results illustrate the sensitivity of the logistics network to demand and capacity changes

Scenario	Transportation Capacity	Warehouse Capacity	Demand	Service Level (%)	Emission Index
Normal	100%	100%	100%	97.2	86.8
High Demand	100%	100%	120%	94.6	93.5
Reduced Transport Capacity	80%	100%	100%	93.8	91.7
Reduced Warehouse Capacity	100%	80%	100%	94.2	90.9
High Demand + Reduced Capacity	80%	80%	120%	89.7	101.6

The scenario results illustrate the sensitivity of the logistics network to demand and capacity changes. High demand combined with reduced transportation and warehouse capacity creates the greatest operational pressure. Under such conditions, the optimization framework can prioritize critical shipments, redistribute available warehouse space, and reassign transportation resources to maintain feasible operations.

6.7 Discussion

The results demonstrate the importance of jointly considering transportation and warehouse capacity rather than treating them as independent resources. The illustrative findings indicate that integrated allocation can improve resource utilization and service performance while reducing environmental impact. The improvement is primarily associated with the interaction between shipment allocation,

warehouse availability, vehicle capacity, and environmental constraints.

The scenario analysis further demonstrates that capacity shortages can significantly influence service performance and environmental efficiency. Consequently, logistics planning should consider both current resource availability and potential variations in demand. The proposed multi-objective framework provides a structured mechanism for evaluating these trade-offs and identifying alternative allocation strategies.

8. Conclusion

This study proposed a multi-objective decision framework for the integrated allocation of transportation and warehouse capacity under operational and environmental constraints. The framework jointly considers transportation cost, warehouse operating cost, capacity utilization, carbon emissions, demand fulfillment, and service-level requirements, thereby addressing the limitations of independent transportation and warehouse planning. A mathematical optimization model was formulated with vehicle-capacity, warehouse-storage, handling-capacity, inventory-balance, demand-fulfillment, environmental, and service-level constraints. The proposed Pareto-based approach provides multiple feasible allocation alternatives and enables the trade-off between economic efficiency, operational utilization, and environmental sustainability to be examined. The illustrative results indicate that integrated allocation can improve transportation and warehouse utilization while maintaining higher service levels and reducing environmental impact compared with independent and cost-oriented allocation strategies. Scenario analysis further demonstrates that demand increases and capacity reductions can substantially influence logistics performance, highlighting the importance of flexible capacity planning. Since the numerical results presented are illustrative, validation using real transportation and warehouse datasets is required. Future research can extend the framework by incorporating stochastic demand, real-time vehicle availability, dynamic warehouse occupancy, traffic conditions, electric vehicles, renewable-energy-powered warehouses, and rolling-horizon optimization to support real-time sustainable logistics decision-making.

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