

# An Optimization Model for a Two-Echelon Remanufacturing Reverse Supply Chain with Carbon Emission Reduction Consideration

Mingxin Hou, Qiaolun Gu\*

School of Economics and Management, Tianjin University of Technology and Education,  
Tianjin 300222, China

\*Corresponding author: tuteguqiaolunlucy@163.com.

---

## Abstract

To address the high level of carbon emissions in the transportation stage of remanufacturing reverse supply chains, this study develops a two-echelon network optimization model that incorporates multiple transportation modes. Two mixed-integer linear programming (MILP) models are formulated with the objectives of minimizing total cost and carbon emissions, respectively. A case study based on the Yangtze River Delta region is conducted to compare road transportation with multimodal transportation. The results indicate that under a single road transportation mode, the cost-minimization and emission-minimization objectives are aligned. In contrast, multimodal transportation achieves approximately a 48.9% reduction in carbon emissions with only a marginal increase in total cost. These findings demonstrate that multimodal transport provides an effective pathway for low-carbon optimization in remanufacturing supply chains.

## Keywords

Remanufacturing Reverse Supply Chain; Multimodal Transportation; Carbon Emissions; Network Optimization.

---

## 1. Introduction

Against the backdrop of intensifying global climate change and increasing resource and environmental constraints, promoting the transition toward low-carbon and circular economic systems has become a key development priority. Remanufacturing, as an important pathway to realizing the circular economy, reduces resource consumption and environmental pollution through the recovery, disassembly, and reprocessing of end-of-life products, and has been widely applied in industries such as automotive and equipment manufacturing. The reverse supply chain serves as the core carrier of remanufacturing activities, and its network structure and operational efficiency directly affect resource recovery performance and environmental outcomes<sup>[1,5]</sup>. Among its components, transportation connects collection, remanufacturing, and market distribution, and represents a major source of system-wide carbon emissions. Therefore, incorporating transportation mode selection and carbon emissions into a unified decision-making framework is of both theoretical and practical significance for achieving low-carbon optimization in remanufacturing reverse supply chains.

Existing studies on supply chain network optimization have mainly focused on facility location and multi-echelon network design. Alidaee et al.<sup>[1]</sup> developed a multi-level supply chain optimization model based on the location-allocation framework and solved complex networks using integer programming approaches. Subsequently, Zhang et al.<sup>[3]</sup> and Ahmadchali et al.<sup>[4]</sup> introduced robust optimization methods to address demand uncertainty and disruptions, thereby enhancing system

stability and resilience. While these studies provide important methodological foundations, they are primarily oriented toward forward supply chains and focus mainly on economic objectives, with relatively limited consideration of environmental factors.

With the growing emphasis on sustainable development, green and closed-loop supply chains have attracted increasing attention. In this context, Abadi et al.<sup>[2]</sup> incorporated carbon emissions into optimization models and achieved coordinated optimization of economic and environmental objectives through multi-objective mixed-integer programming. Izadian et al.<sup>[5]</sup> further extended model structures from the perspectives of reliability and uncertainty to enhance adaptability under complex conditions. In addition, Bastos et al.<sup>[8]</sup> explored low-carbon pathways in supply chains from a digitalization perspective, highlighting the role of information technology in emission reduction. At the transportation and distribution level, Ye et al.<sup>[10]</sup> introduced carbon constraints into multi-depot vehicle routing problems to balance efficiency and environmental performance. Nevertheless, most of these studies focus on general closed-loop supply chains, with insufficient attention to remanufacturing reverse supply chains.

At the transportation decision level, existing studies mainly focus on route optimization and efficiency improvement. Peng<sup>[6]</sup> developed a multi-objective routing model considering fuzzy time windows to enhance logistics service performance, while Zizi et al.<sup>[16]</sup> incorporated machine learning techniques into dynamic routing optimization, demonstrating effectiveness in reducing transport distance and energy consumption. However, such studies are generally based on the assumption of a single transportation mode and lack a systematic representation of coordinated multimodal decision-making. Furthermore, from the perspective of low-carbon transportation systems, previous research has shown that different transport modes exhibit significant differences in emission intensity, and optimizing the transport structure can effectively reduce overall emissions. Luan et al.<sup>[14]</sup> examined low-carbon transition pathways from a regional transport system perspective, while Khujamberdiev et al.<sup>[11]</sup> and Victor et al.<sup>[12]</sup> explored the potential of clean fuels and hydrogen energy in reducing transport emissions. In addition, Ram et al.<sup>[7]</sup> and Ali et al.<sup>[9]</sup> provided complementary analyses from the perspectives of carbon cycling and energy efficiency. Nevertheless, these studies are largely conducted at a macro level and lack integration with supply chain network optimization models, limiting their applicability to practical decision-making.

In summary, although substantial progress has been made in supply chain network optimization and low-carbon transportation, several limitations remain. First, most studies focus on forward or general closed-loop supply chains, with limited attention to remanufacturing reverse supply chains. Second, transportation modes are often simplified as a single option, lacking systematic modeling and optimization of multimodal transport. Third, the coupling relationship between network structure and carbon emissions has not been fully explored. Fourth, there is a lack of quantitative comparative analysis on how different transportation modes affect system cost and carbon emissions.

To address these gaps, this study focuses on remanufacturing reverse supply chains and develops a two-echelon network optimization model that incorporates multiple transportation modes. Within a unified framework, transportation routes and mode selection are jointly optimized, and two mixed-integer programming models are formulated with the objectives of minimizing total cost and carbon emissions. Through a case study in a representative region, the network structure and operational performance under road-only and multimodal transport scenarios are compared. The study systematically reveals the impact of transportation mode selection on cost and emissions, providing both theoretical support and practical guidance for low-carbon transportation decision-making in supply chains.

## 2. Notation and Model Assumptions

The symbols used in the proposed two-echelon remanufacturing reverse supply chain network optimization model are summarized in Table 1.

**Table 1.** Notation and definitions

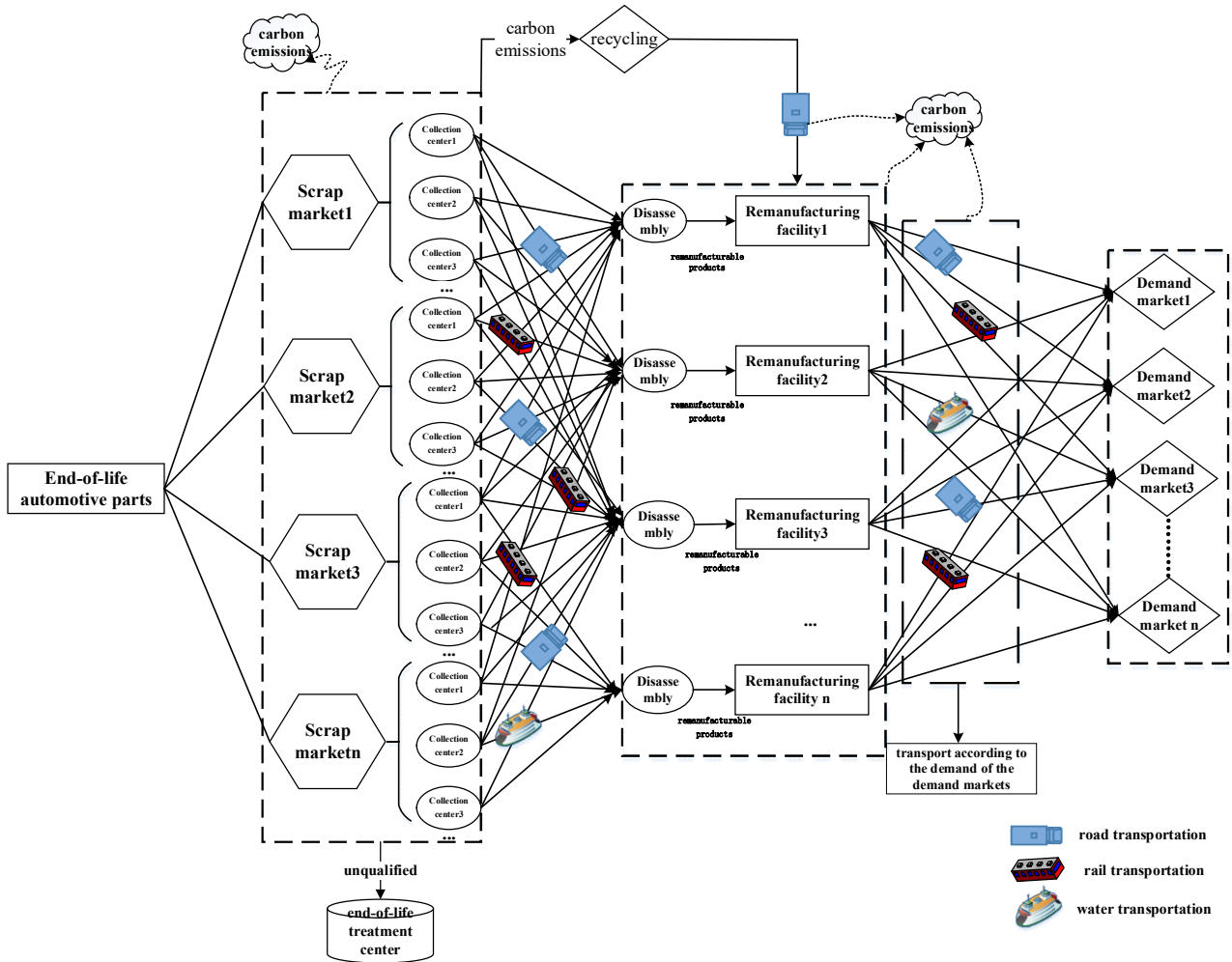
Category	Symbol	Definition
Sets	$I$	Set of collection centers, $i \in I$
	$K$	Set of candidate remanufacturing facilities, $k \in K$
	$M$	Set of demand markets, $m \in M$
	$T$	Set of transportation modes, $t \in T$
Decision variables	$x_{ik}^t$	Quantity of used products transported from collection center $i$ to remanufacturing facility $k$ using transportation mode $t$ (units)
	$y_{km}^t$	Quantity of remanufactured products transported from facility $k$ to demand market $m$ using transportation mode $t$ (units)
Parameters	$C_{ik}^t$	Unit transportation cost from collection center $i$ to facility $k$ using mode $t$ (RMB/unit)
	$C_{km}^t$	Unit transportation cost from facility $k$ to market $m$ using mode $t$ (RMB/unit)
	$d_{ik}$	Distance from collection center $i$ to facility $k$ (km)
	$d_{km}$	Distance from facility $k$ to market $m$ (km)
	$E_t$	Carbon emission factor of transportation mode $t$ (kg CO <sub>2</sub> e/km unit)
	$F_k$	Fixed cost of establishing facility $k$ (RMB)
	$P_k$	Unit processing cost at facility $k$ , including disassembly and remanufacturing (RMB/unit)
	$P_k^e$	Carbon emissions per unit processed at facility $k$ (kg CO <sub>2</sub> e/unit)
	$S_i$	Quantity of collected used products at collection center $i$ per quarter (units/quarter)
	$D_m$	Demand at market $m$ per quarter (units/quarter)
	$R_k$	Maximum processing capacity of facility $k$ per quarter (units/quarter)

Figure 1 illustrates the two-echelon remanufacturing reverse supply chain aimed at enhancing carbon emission reduction performance. The network considered in this study consists of three types of nodes: collection centers, remanufacturing facilities, and demand markets. Collection centers are responsible for gathering end-of-life products, which are then transported to remanufacturing facilities for disassembly and processing. The remanufactured products are subsequently delivered to demand markets. Multiple transportation modes, including road, rail, and water, can be employed in the transportation process.

The following assumptions are made in this study:

- (1) Deterministic supply and demand: The demand at each market  $D_m$  and the quantity of collected products at each collection center  $S_i$  are assumed to be stable and predictable within the planning horizon.
- (2) Integrated disassembly and remanufacturing: Disassembly is carried out within remanufacturing facilities, and no separate disassembly centers are considered.
- (3) Fixed emission factors: The carbon emission factors for different transportation modes are based on the 2024 Chinese industry standards, while the processing emission factor of remanufacturing facilities is determined according to industry average levels.

- (4) Capacity constraints: The maximum processing capacity of each candidate remanufacturing facility  $k$  is limited to  $R_k$ .
- (5) Distance-based transportation cost: Transportation costs are standardized based on distance. To examine the impact of different decision objectives on the network structure, two single-objective optimization models are developed, namely cost minimization and carbon emission minimization<sup>[13]</sup>.



**Figure 1.** Two-echelon remanufacturing reverse supply chain for enhancing carbon emission reduction performance

(1) Minimize total cost:

$$\min Z_1 = \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} c_{ik}^t x_{ik}^t + \sum_{k \in K} \sum_{m \in M} \sum_{t \in T} c_{km}^t y_{km}^t + \sum_{k \in K} P_k \sum_{i \in I} \sum_{t \in T} x_{ik}^t \quad (1)$$

(2) Minimize carbon emissions:

$$\min Z_2 = \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} (d_{ik} \cdot E_t \cdot x_{ik}^t) + \sum_{k \in K} \sum_{m \in M} \sum_{t \in T} (d_{km} \cdot E_t \cdot y_{km}^t) + \sum_{k \in K} P^e \sum_{i \in I} \sum_{t \in T} x_{ik}^t \quad (2)$$

(3) Constraints

$$s.t. \begin{cases} \sum_{k \in K} \sum_{t \in T} x_{ik}^t = S_i, \forall i \in I \\ \sum_{i \in I} \sum_{t \in T} x_{ik}^t \leq R_k \cdot v_k, \forall k \in K \\ \sum_{k \in K} \sum_{t \in T} y_{km}^t \geq D_m, \forall m \in M \\ \sum_{m \in M} \sum_{t \in T} y_{km}^t = \sum_{i \in I} \sum_{t \in T} x_{ik}^t, \forall k \in K \end{cases} \quad (3)$$

### 3. Model Solution and Case Analysis

A case study of automotive parts remanufacturing in the Yangtze River Delta region is conducted. Nanjing, Suzhou, Wuxi, and Changzhou are selected as collection centers; Xuzhou, Lianyungang, and Huai’an are candidate remanufacturing facilities, with Xuzhou and Huai’an chosen as fixed remanufacturing plants; Shanghai, Hangzhou, Hefei, and Ningbo are demand markets. Distances, unit transportation costs, and carbon emission factors between nodes are obtained from the API, industry standards, and survey data. Collection quantities and demand are estimated based on statistical yearbooks and industry reports.

#### 3.1 Optimization Results under Road-only Transportation

In the scenario where only road transportation is allowed, the cost-minimization and emission-minimization objectives are solved separately. Using Lingo 18.0 to solve the mixed-integer linear programming model, the minimum total cost is 1,166,077.1 RMB; when minimizing carbon emissions, the minimum emission is 277,521.6 kg CO<sub>2</sub> e. The specific flow allocations between nodes are exactly the same as those of the cost-minimization solution, as shown in Table 2.

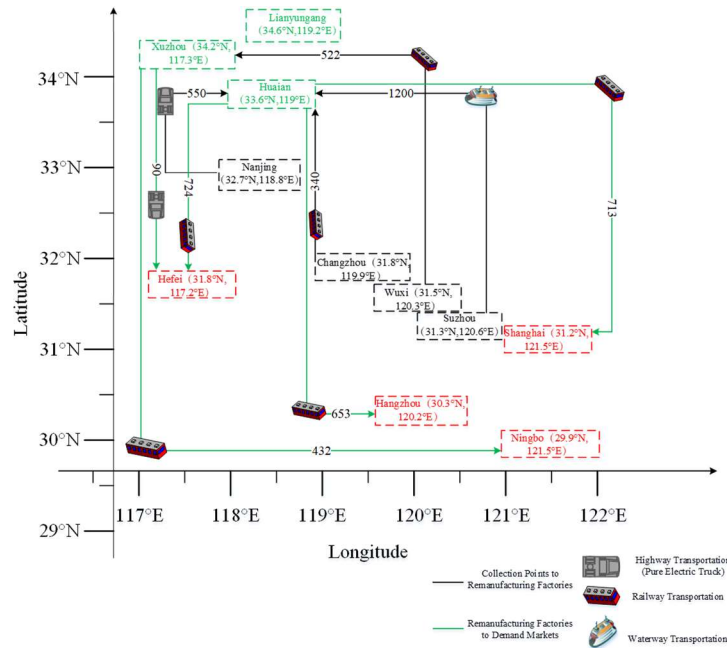
**Table 2.** Flow allocation under cost and emission minimization with road-only transportation (units: pieces)

Node Type	Specific Node	Remanufacturing Facility			
		Xuzhou(K <sub>1</sub> )	Lianyungang(K <sub>2</sub> )	Huai’an(K <sub>3</sub> )	—
Collection center	Nanjing(I <sub>1</sub> )	/	/	550	/
	Suzhou(I <sub>2</sub> )	/	/	972	/
	Wuxi(I <sub>3</sub> )	750	/	/	/
	Changzhou(I <sub>4</sub> )	/	/	340	/
Node Type	Specific Node	Demand Market			
		Shanghai(M <sub>1</sub> )	Hangzhou(M <sub>2</sub> )	Hefei(M <sub>3</sub> )	Ningbo(M <sub>4</sub> )
Remanufacturing facility	Xuzhou(K <sub>1</sub> )	/	/	750	/
	Lianyungang(K <sub>2</sub> )	/	/	/	
	Huai’an(K <sub>3</sub> )	713	653	64	432

Further analysis reveals that in this scenario, the optimal flow allocations under cost minimization and emission minimization are identical, indicating that when only one transportation mode is available, transportation distance and carbon emissions are highly positively correlated, and the two objectives are consistent.

### 3.2 Optimization Results under Multimodal Transportation

In the multimodal scenario where road, rail, and water transport are allowed in combination, the proposed model is re-solved. The unit carbon emission factors for each mode are: road 0.1697, rail 0.0288, water 0.0152 kg CO<sub>2</sub> e/km. Minimizing carbon emissions yields a minimum system emission of 141,867.7 kg CO<sub>2</sub> e, with a corresponding total cost of 1,167,265.1 RMB. The flow allocation under multimodal transportation is shown in Figure 2. Compared with road-only transport, medium- and long-distance shipments shift from road to rail or water, significantly reducing carbon emissions.



**Figure 2.** Flow allocation between nodes under multimodal transportation

### 3.3 Comparative Analysis of Road-only and Multimodal Transportation

Based on the optimization results under the two transport modes, this section compares cost, carbon emissions, and flow structure, as shown in Table 3.

**Table 3.** Comparison of indicators between the two transport modes

Indicator	Road-only	Multimodal	Change rate
Total cost (RMB)	1,166,077.1	1,167,265.1	+0.1%
Total carbon emissions (kg CO <sub>2</sub> e)	277,521.6	141,867.7	-48.9%
Medium-/long-distance mode	Primarily road	Primarily rail/water	—
Flow structure (collection to plant)	Short-haul concentration	Long-haul multimodal	—

As shown in Table 3, compared with road-only transport, multimodal transport achieves approximately a 48.9% reduction in carbon emissions with only a 0.1% increase in total cost. This indicates that through rational combination of transport modes, environmental performance can be significantly improved with almost no economic sacrifice. The underlying mechanism is the marked difference in unit carbon emission intensity among transport modes. Although road transport offers higher flexibility and timeliness, its emission intensity is high; rail and water transport have clear low-carbon advantages for medium and long-haul distances. In the multimodal model, optimization decisions shift medium and long-haul shipments from road to rail/water, effectively reducing

system-wide emissions. Meanwhile, road transport is retained for short distances to ensure efficiency and connectivity, forming a “low-carbon trunk, efficient branch” transport structure. From the optimization perspective, under road-only transport, both cost and emissions are positively correlated with distance, so the two objective functions are consistent, leading to identical optimal solutions. Under multimodal transport, however, differences in cost and emission characteristics among modes provide greater optimization space, enabling synergistic optimization of cost and emissions.

In summary, multimodal transport can significantly reduce carbon emissions in the remanufacturing reverse supply chain while controlling cost increases within a reasonable range, representing an important pathway for green supply chain optimization.

#### 4. Conclusion and Future Work

Focusing on carbon emission reduction in the transportation stage of a remanufacturing reverse supply chain, this paper develops a two-echelon network optimization model that incorporates multiple transport modes. Through a case study, the operational performance under different transport modes is compared. The main conclusions are as follows:

- (1) Transport mode has a decisive impact on carbon emissions. Under road-only transport, both cost and emissions show strong consistency with distance, making the cost-optimal and emission-optimal solutions coincide. This indicates that the scope for low-carbon optimization is limited when only a single mode is available.
- (2) Multimodal transport can significantly enhance the system’s carbon reduction capability. Compared with road-only transport, multimodal transport shifts medium- and long-distance shipments from road to rail/water, achieving about a 48.9% emission reduction with almost no increase in total cost, demonstrating significant environmental benefits from synergistic mode allocation.
- (3) There is a weak trade-off between cost and carbon emissions. The case results show that with a proper configuration of transport modes, the system can achieve “low carbon without significant cost increase,” meaning that through coordinated optimization of network structure and transport mode selection, the conflict between economic and environmental objectives can be effectively mitigated.
- (4) Optimizing the transport structure is a key pathway to low-carbon goals. The “short-haul road + medium/long-haul rail/water” structure formed under multimodal transport helps reduce emission intensity per unit of transport while maintaining efficiency.

Based on these findings, the following decision support can be provided to enterprises and governments:

- (1) Enterprises should prioritize building a multimodal transport system, rationally allocating different transport modes, and increasing the share of rail and water transport especially for medium- and long-haul distances.
- (2) In remanufacturing network planning, carbon emissions should be incorporated as a decision objective to achieve synergistic optimization of transport routes and mode selection.
- (3) Governments should guide enterprises toward low-carbon transport transitions by improving rail and water infrastructure and providing multimodal transport subsidies.

Although this study has achieved certain results, future work may consider the randomness of collection quantities and demand by introducing robust optimization or stochastic programming methods to improve practical applicability, and incorporate factors such as transport time and service level to build a more realistic comprehensive decision model.

#### Acknowledgments

This work was supported by the Tianjin Philosophy and Social Sciences Planning (Key Project) under Grant number TJGL24-007.

## References

- [1] Alidaee, B., & Wang, H. (2026). Multilevel facility location optimisation: a novel integer programming formulation and approaches to heuristic solutions. *International Journal of Production Research*, 64(6), 2087–2108.
- [2] Abadi, H. A. M., Saraswat, K., Adhikari, S., et al. (2025). Designing a Sustainable Multi-Objective Mixed-Integer Linear Programming (MILP) Model for Shrimp Supply Chains. In *IISE Annual Conference Proceedings* (pp. 1–6).
- [3] Zhang, W., Huang, C., Gao, J., et al. (2025). Robust location-allocation decision considering casualty prioritization in multi-echelon humanitarian logistics network. *Information Sciences*, 695, 121731.
- [4] Ahmadchali, A. M., Afrouzi, E. M., Javadian, N., et al. (2024). A robust location-allocation model for optimizing a multi-echelon blood supply chain network under uncertainty. *OPSEARCH*, Advance online publication, 1–53.
- [5] Izadian, B. A., Pasandideh, R. H. S., & Abad, K. K. R. A. (2024). A new approach for reliability modeling in green closed-loop supply chain design under post-pandemic conditions: A case study. *Computers & Chemical Engineering*, 189, 108803.
- [6] Juanjuan, P. (2023). Effectiveness of Mixed Fuzzy Time Window Multi-objective Allocation in E-Commerce Logistics Distribution Path. *International Journal of Computational Intelligence Systems*, 16(1).
- [7] Ram, P. S. A., Billard, H., Perriere, F., et al. (2026). Viral and grazer regulation of bacterial mediated carbon cycling in a temperate eutrophic freshwater ecosystem. *Limnologica*, 118, 126334.
- [8] Bastos, T., Teixeira, L., & Nunes, R. J. L. (2025). Digitalization of the residual biomass supply chain: A sustainable analysis of the current state using a hybrid model approach. *Energy Sources, Part B: Economics, Planning, and Policy*, 20(1).
- [9] Ali, S. S., Hossain, S. S., & Mohsin, A. M. (2025). Sustainable and Cost-Effective Cooling: A Case Study of Night-Time Heat Pump Operation and Thermal Energy Storage Integration. *Journal of Chemical Engineering of Japan*, 58(1).
- [10] Ye, B., Wang, Y., Lei, X., et al. (2025). Multi-Depot Vehicle Routing Problem with Collaborative Replenishment Using ALNS–ABC Algorithm. *International Journal of Software Engineering and Knowledge Engineering*, 36(4).
- [11] Khujamberdiev, R., & Cho, M. H. (2025). Hybrid Fuels for CI Engines with Biofuel Hydrogen Ammonia and Synthetic Fuel Blends. *Energies*, 18(11), 2758. <https://doi.org/10.3390/en18112758>
- [12] Victor, N., & Nichols, C. (2024). Future of hydrogen in the U.S. energy sector: MARKAL modeling results. *Applications in Energy and Combustion Science*, 18, 100259.
- [13] Costa, R. O., Marquet, O., Fu, X., et al. (2026). A longitudinal study on the emotional and behavioural impacts of banning e-scooters on public transport. *Transportation Research Interdisciplinary Perspectives*, 37, 101963.
- [14] Luan, S., Ma, J., Gan, D., et al. (2026). Decarbonizing regional air transport: Strategic pathways for sustainable multi-airport systems in developing economies. *Journal of Air Transport Management*, 135, 103023.
- [15] Batikh, S. A., Alzahrani, A. Y., Battikh, S. M., et al. (2026). A framework for multi-target temperature profile generation using functional PCA and Gaussian mixture models for Fire PRA. *Annals of Nuclear Energy*, 235, 112333.
- [16] Zizi, M., Hmamou, Y., Chafi, A., et al. (2026). Dynamic route optimization in smart logistics using hybrid machine learning models. *Smart and Resilient Transportation*, 8(1), 79–100.