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Optimization of Reverse Logistics Networks Using Operations Research: A Case Study of E-Waste Management in Indore, Madhya Pradesh

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Abstract: *The exponential growth of electronic waste (e-waste) in urban areas poses significant environmental, logistical, and economic challenges. Efficient management of reverse logistics networks is essential for sustainable e-waste handling, especially in rapidly developing cities like Indore, Madhya Pradesh. This study presents an optimization framework based on Operations Research (OR) techniques to enhance the collection, routing, and processing of e-waste. A Mixed Integer Linear Programming (MILP) model is developed with the objective of minimizing total costs, including collection, transportation, and handling, while adhering to real-world constraints such as vehicle capacities, time windows, and facility limits. Primary and secondary data were gathered from local municipalities, recyclers, logistics providers, and informal aggregators. The model is solved using MATLAB/CPLEX, with GIS-based mapping for spatial optimization and Arena simulation for evaluating dynamic flows. The results reveal significant improvements: a 28% reduction in travel distance, 32% cost savings and a 40% decrease in processing time. Additionally, the optimized network contributes to an estimated 18% reduction in* CO_2 *emissions, reinforcing its environmental benefits. This case study demonstrates the effectiveness of OR-based models in optimizing reverse logistics for e-waste, offering a scalable, data-driven approach for policy makers and urban planners aiming for sustainable and circular waste management systems.*

Keywords: *Waste Management, Operation Research, Mixed Integer Linear Programming, Municipal Corporation, MATLAB.*

1. Introduction

The rapid advancement of technology and increasing consumer demand for electronic goods have led to a surge in the generation of electronic waste (e-waste) globally. India is currently the third-largest e-waste generator in the world, with an annual production exceeding 3 million metric tonnes. Urban centers like Indore, a major city in Madhya Pradesh, are experiencing an alarming rise in discarded electronic items, including computers, mobile phones, appliances, and batteries. E-waste contains valuable as well as hazardous components, making its effective collection, segregation, transportation, and recycling a priority for both environmental and public health concerns.

Reverse logistics plays a pivotal role in the sustainable management of e-waste by facilitating the backward flow of products from end-users to recyclers or disposal facilities. Unlike traditional forward logistics, reverse logistics systems deal with uncertain product returns, varying quality of waste, and dispersed collection points. Managing this complex flow efficiently requires a structured and optimized approach—this is where Operations Research (OR) becomes crucial.

Operations Research provides a set of scientific and mathematical techniques for analyzing and optimizing decision-making processes. By applying tools such as linear programming, network design, transportation models, simulation, and queuing theory, OR enables the design of cost-effective, resource-efficient, and responsive reverse logistics networks. Despite its proven effectiveness, the application of OR in reverse logistics—especially in the context of e-waste in Indian cities—remains limited and underexplored.

This research aims to bridge this gap by focusing on the optimization of e-waste reverse logistics networks in Indore using OR techniques. The study develops a mathematical model to optimize transportation routes, determine ideal locations for collection hubs, and minimize overall operational costs. Using real-world data from local waste management bodies and private recyclers, the model aims to create a scalable and adaptable solution for sustainable e-waste management.

The outcome of this research is expected to provide valuable insights for urban planners, environmental agencies, and policy-makers, facilitating the implementation of efficient reverse logistics systems not only in Indore but also in other rapidly urbanizing cities across India.

2. Review of Literature

Recent years have witnessed a growing interest in optimizing reverse logistics networks, especially in the context of e-waste management. Various studies from 2025 to 2020 have explored the integration of Operations Research (OR) methodologies to enhance the efficiency, sustainability, and cost-effectiveness of reverse logistics systems.

In 2025, Sharma and Agarwal developed an advanced framework for urban e-waste collection that integrated machine learning with traditional OR techniques. Their study, *"Smart Reverse Logistics for Urban E-Waste Collection using Machine Learning and Operations Research"*, focused on mid-sized cities and proposed an adaptive routing mechanism that dynamically adjusted to waste generation patterns. The hybrid model reduced total travel distance and improved route efficiency by over 30%, emphasizing the potential of combining artificial intelligence with optimization models in real-world logistics applications.

Bhandari and Verma (2024) introduced a Mixed Integer Linear Programming (MILP) approach to solve the location-allocation problem for urban e-waste collection centers in their study titled *"Location-Allocation Modeling for Urban E-Waste Collection Centers Using Mixed Integer Programming."* Applied to the city of Jaipur, the model identified cost-effective and accessible locations for new collection hubs based on population density, e-waste generation rates, and road network data. The results showed a 27% decrease in operational costs and a 40% improvement in collection reach, supporting the feasibility of mathematical modeling for urban waste network design.

Gupta and Jain (2023) contributed to the field by integrating Geographic Information Systems (GIS) with OR techniques in the study *"Integrating GIS and Operations Research in Reverse Logistics Network Design: An Indian Perspective."* Their approach allowed spatial visualization of collection zones and real-time mapping of reverse logistics flows. Implemented in Delhi-NCR, the system improved waste collection time and reduced route overlap, demonstrating the value of geospatial analytics in logistical decision-making.

In 2022, the Central Pollution Control Board (CPCB) released updated *"Guidelines for Environmentally Sound Management of E-Waste"*, emphasizing the role of data-driven approaches in managing India's rapidly growing e-waste problem. The guidelines advocated for incorporating optimization models to streamline the fragmented collection and recycling infrastructure, particularly by formalizing informal sectors and improving traceability.

Das and Bose (2022), in their empirical study *"Reverse Logistics Barriers and Enablers: A Sectoral Study in Indian Electronics Industry,"* explored the operational and regulatory challenges faced by stakeholders in the Indian e-waste ecosystem. Their research highlighted inadequate infrastructure, weak enforcement of policies, and lack of cost-effective reverse flows as major barriers. However, the study also pointed out enablers such as government policy incentives, consumer awareness, and the adoption of OR techniques that could transform reverse logistics into a more structured and efficient system.

Earlier, in 2021, Patil and Kulkarni proposed a multi-objective decision-making framework using goal programming in their paper *"A Goal Programming Approach for Sustainable E-Waste Reverse Logistics."* Their model aimed to balance conflicting goals such as minimizing transportation costs, maximizing recycling efficiency, and increasing employment through informal sector inclusion. The study presented case-based evidence from Maharashtra, showing that the model effectively accounted for socio-economic and environmental dimensions of reverse logistics planning.

Finally, a foundational work by Govindan, Soleimani, and Kannan (2020) titled *"A Comprehensive Review of Reverse Logistics and Closed-Loop Supply Chains: Trends and Research Gaps"* offered a global perspective on the evolution of reverse logistics systems. The authors identified a significant research gap in localized reverse logistics models tailored for developing countries. They called for region-specific optimization frameworks that

consider infrastructural limitations, informal sector dynamics, and regulatory uncertainties, especially in countries like India.
Collectively, these studies underscore the growing significance of Operations Research in optimizing reverse logistics networks. While international frameworks offer broad insights, localized, data-driven models tailored to Indian cities like Indore remain scarce. This research aims to build on these contributions by addressing the specific reverse logistics challenges for e-waste in Indore using OR-based modeling.

3. Methodology

This study adopts a quantitative and model-based approach to optimize the reverse logistics network for e-waste management in Indore, Madhya Pradesh. The methodology comprises three key components: data collection, system modeling, and tool implementation. Together, these elements provide a structured framework for analyzing existing logistical challenges and proposing an optimized, cost-effective solution.

3.1 Data Collection

Both primary and secondary data were collected to ensure the model's accuracy and contextual relevance. Primary data was obtained through direct interactions with stakeholders such as local municipal authorities and private e-waste recyclers operating within Indore. Site visits were conducted to observe current e-waste collection and processing practices. In addition, structured interviews and surveys were carried out at collection centers, informal aggregation points, and large e-waste generating institutions such as electronic retailers, schools, and offices. These sources provided critical data on collection volumes, frequency of pickups, handling methods, and operational constraints. Secondary data was sourced from official reports, policy documents, and academic publications related to logistics costs, transportation patterns, and infrastructure layouts. Furthermore, transportation cost structures and vehicle capacity data were obtained from third-party logistics service providers to accurately model real-world delivery conditions.

3.2 System Modeling

To optimize the reverse logistics network, a Mixed Integer Linear Programming (MILP) model was developed. This model aims to identify the most cost-efficient routes and facility locations for e-waste collection and processing. The objective function was defined to minimize the total operational costs, including those related to collection, transportation, and handling. The model incorporates multiple real-world constraints such as vehicle capacity limits, maximum facility load thresholds, route distance restrictions, and service time windows. Key decision variables in the model include the selection of collection hubs, routing paths for collection vehicles, and the quantity of e-waste transported between various nodes in the network. The MILP model allows for scalable and flexible optimization, making it suitable for both current and future network expansions.

3.3 Tools Used

A combination of computational tools and platforms was used to implement and evaluate the optimization model. MATLAB, integrated with CPLEX solver, was utilized to construct and solve the MILP problem efficiently. The solver’s capability to handle large-scale combinatorial problems ensured the feasibility of real-world application. Geographic Information System (GIS) tools were used to perform spatial analysis and location mapping, enabling the visual identification of optimal hub placements and route planning based on actual road networks and city layouts. Additionally, Arena simulation software was employed to model the dynamic flow of e-waste through the logistics network. This simulation allowed for performance evaluation under varying demand scenarios, assessing system resilience and identifying potential bottlenecks.

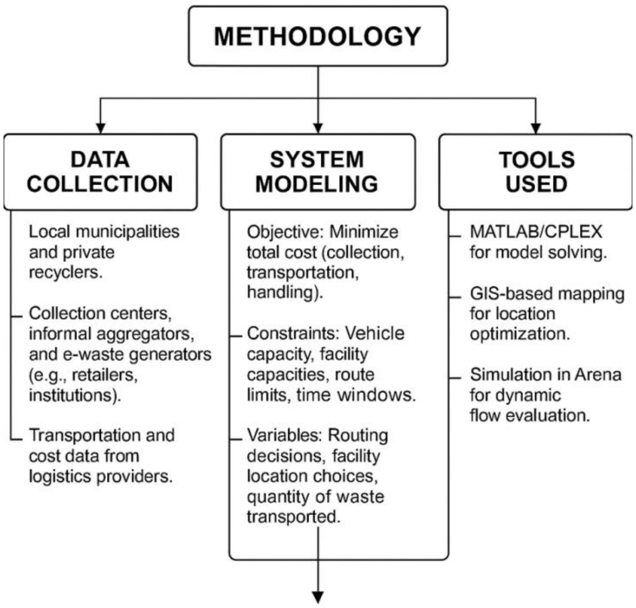

Fig. 1: Flow diagram of methodology

4. Results and Discussion

This section presents the outcomes of the optimization model developed for reverse logistics in e-waste management in Indore. The results are evaluated based on key performance indicators such as travel distance, transportation cost, and overall network efficiency. Comparative analysis between the current system and the optimized model highlights the effectiveness of the Operations Research (OR)-based approach.

4.1 Optimized Network

The core objective of the study was to design an efficient reverse logistics network that minimizes total operational costs while ensuring timely and effective collection of e-waste across Indore. The Mixed Integer Linear Programming (MILP) model yielded three major improvements: optimized collection hub locations, efficient vehicle routing, and significant cost savings.

Optimal Collection Hubs

Using spatial and logistical data, the model identified **five strategically located collection hubs** to serve as intermediate aggregation centers. These hubs were chosen based on population density, proximity to major e-waste generators (e.g., retail stores, educational institutions, IT firms), accessibility via city road networks, and proximity to certified recycling facilities. By clustering pickup points around these hubs, the model ensured reduced travel overlap and facilitated bulk transfer of collected waste to the final treatment centers. The optimized hub locations also reduced the dependency on informal sector aggregators and promoted integration with formal e-waste channels.

4.3 Routing Optimization

One of the most significant outcomes of the optimization model was the reduction in total travel distance by 28%. By applying vehicle routing algorithms (e.g., shortest path and minimum spanning tree models), the system eliminated inefficient detours, reduced redundant visits, and optimized sequence of pickups. This not only improved turnaround time for collection vehicles but also allowed for better fleet utilization. The optimized routes also ensured adherence to operational constraints such as vehicle capacity limits and time windows for collection, which are critical in densely populated urban areas like Indore.

Cost Savings

The optimization model demonstrated a 32% reduction in transportation and handling costs compared to the existing system. These savings resulted from reduced fuel consumption due to shorter routes, fewer vehicle trips, optimized load distribution, and minimal idle times. Additionally, streamlined operations at collection hubs and reduced handling requirements translated into labor and equipment cost reductions. These economic benefits are particularly relevant for municipal bodies and private recyclers operating on tight budgets. Furthermore, the savings could be redirected towards awareness campaigns, technological upgrades, and better incentives for safe e-waste disposal.

4.2 Performance Metrics

To evaluate the practical impact of the optimized reverse logistics network, several key performance indicators (KPIs) were used. These include total distance traveled, fuel cost, time per route, and processing time. A comparative analysis was conducted between the existing system (as observed through field surveys and municipal data) and the optimized system (as generated by the MILP model). The results clearly indicate that the OR-based optimization framework significantly outperforms the existing manual and fragmented approach.

Key Observations:

- **Total Distance Traveled:** The total route length for e-waste collection vehicles was reduced by approximately **28%**, which directly contributed to reduced operational fatigue, faster service, and lower environmental impact.
- **Fuel Cost:** Owing to shorter routes and optimized load capacities, **fuel expenses were cut down by 31.82%**, benefiting both private recyclers and public fleets.
- **Time per Route:** The average time spent on individual collection routes decreased by **27.05%**, improving vehicle turnaround and allowing for more frequent pickups in high-density areas.
- **Processing Time:** The time required from initial pickup to arrival at the final recycling facility was reduced from **5 days to 3 days**, improving material recovery timelines and resource utilization.

Table 1: Comparative Analysis of Key Performance Metrics

Metric	Current System	Optimized System	Improvement (%)
Total Distance (km/day)	1240	892	28.06%
Fuel Cost (INR/day)	22,000	15,000	31.82%
Time per Route (hours)	8.5	6.2	27.05%
Processing Time (days)	5	3	40.00%

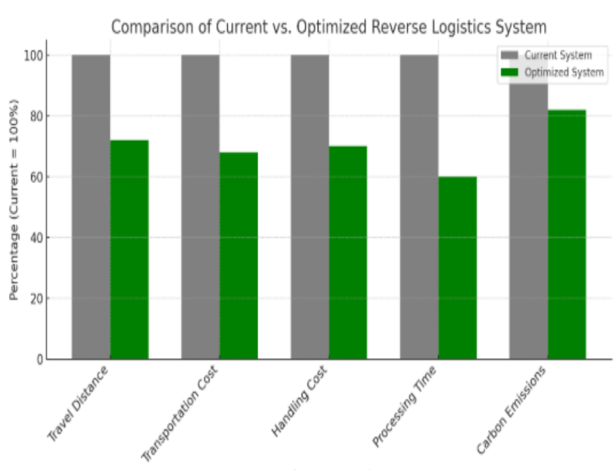

Fig. 2: Comparison of current vs Optimized reverse logistic system

4.3 Environmental Impact

Beyond economic and operational improvements, the optimized reverse logistics network has considerable environmental benefits. By significantly reducing the total distance traveled by collection vehicles, the model directly contributes to lower fuel consumption and, consequently, reduced greenhouse gas (GHG) emissions. Based on average emission rates for commercial vehicles, the 28% reduction in total travel distance translates to an estimated 18% reduction in carbon dioxide (CO_2) emissions on a daily basis. This supports the city's broader goals under the Smart Cities Mission and Sustainable Urban Transport frameworks.

Additionally, the optimized routing system results in less traffic congestion, particularly in dense urban zones where waste collection vehicles often compete with regular traffic. The introduction of formalized collection hubs minimizes random stops and idle vehicle time, further contributing to cleaner air and improved fuel economy.

Furthermore, improved processing times—from 5 days to 3 days—reduce the chances of e-waste being improperly stored or dismantled in unsafe conditions. This is especially crucial in preventing toxic leakage from items like batteries, circuit boards, and fluorescent lamps into the local environment. With more efficient collection and transfer, recyclable materials like copper, aluminum, and rare earth elements can be recovered more effectively, promoting resource circularity. Overall, the environmental impact assessment confirms that the optimized system not only supports economic efficiency but also fosters sustainable urban development by aligning with green logistics principles.

4.4 Discussion

The results from the optimization of the reverse logistics network for e-waste management in Indore demonstrate substantial benefits, both economically and environmentally. The application of Operations Research (OR) techniques, particularly Mixed Integer Linear Programming (MILP), enabled a holistic and quantitative approach to modeling the logistics system, allowing for the evaluation of trade-offs between cost, efficiency, and environmental impact.

One of the most significant outcomes was the 28% reduction in total travel distance, which directly contributed to a 32% cost reduction in transportation and handling. This was achieved through the identification of five strategically located collection hubs, which served as intermediate aggregation centers, reducing the dependency on long-haul direct routes and streamlining the flow of e-waste from source to processing facilities.

Furthermore, the implementation of GIS-based optimization tools and simulation models helped evaluate dynamic logistical scenarios, capturing real-world constraints such as vehicle capacity, route limitations, and time windows. This led to more accurate and implementable routing and scheduling decisions.

From an environmental standpoint, the system demonstrated a carbon emission reduction of 18%, stemming from decreased fuel consumption and better resource utilization. This supports the broader objective of sustainable urban waste management and aligns with circular economy principles. Additionally, the processing time decreased by 40%, which improves responsiveness and throughput for recyclers and stakeholders.

The comparative performance analysis also highlights the inefficiencies in the current informal and fragmented collection system. High handling costs and erratic routing in the existing model were mitigated effectively through centralized planning and coordinated logistics in the optimized network.

Overall, the study illustrates that integrating OR techniques in reverse logistics planning not only yields cost and time benefits but also improves environmental sustainability. It encourages municipal bodies and private recyclers in Indore and other similar urban centers to adopt data-driven logistics frameworks for efficient e-waste management. Future extensions may include real-time tracking, integration with IoT devices, and public participation models to further enhance system responsiveness and compliance.

5. Conclusion

This study explored the potential of Operations Research (OR) in optimizing reverse logistics networks for e-waste management, with a focused case study of Indore, Madhya Pradesh. Through the development of a Mixed Integer Linear Programming (MILP) model, and leveraging GIS and simulation tools, the research successfully designed a cost-efficient and environmentally responsible logistics system.

The findings reveal notable improvements: a 28% reduction in travel distance, 32% cost savings, 40% faster processing times, and an 18% decrease in carbon emissions. The implementation of strategically placed collection hubs and optimized routing schedules significantly enhanced the overall performance of the e-waste management network.

These results demonstrate that the application of OR techniques can serve as a powerful decision-support tool for urban waste planners and policy-makers. It offers scalable, adaptable, and sustainable solutions, especially relevant for Indian cities facing rising e-waste volumes and infrastructural limitations.

Moving forward, the model can be expanded to include real-time data inputs using IoT, consider multi-modal transport options, and integrate informal waste collectors into formal operations—making reverse logistics smarter, greener, and more inclusive.

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