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OPTIMIZING GREEN TRANSPORTATION BY USING OPERATIONS RESEARCH IN SUSTAINABLE ROAD LOGISTICS

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Abstract

Despite rapid advancements in air, rail, and maritime transport, road transportation continues to serve as the cornerstone of global logistics and passenger movement. However, it remains one of the largest consumers of fossil fuels and a leading contributor to greenhouse gas emissions. As concerns surrounding climate change and environmental sustainability intensify, the need to transition towards eco-friendly transportation models becomes paramount. While green transportation has emerged as a multidisciplinary solution, the strategic potential of Operations Research (OR) in driving this transformation remains significantly underexplored. This paper emphasizes the critical role of OR in improving the efficiency and sustainability of road transportation systems. It explores major OR techniques such as the Vehicle Routing Problem (VRP), supply chain reengineering, and Intelligent Transportation Systems (ITS), supported by models, numerical examples, and graphical analysis.

Keywords: Transportation Problem (TP), Operation Research (OR), Vehicle Routing Problem (VRP), Supply Chain Re-Engineering, Intelligent Transportation Systems (ITS), Green Transportation.

1. INTRODUCTION

The transportation industry, charged with the duty of hauling millions of tons of products and millions of travelers every day, is still an indispensable backbone to world economic and industrial progress. Despite technological progress and the rise of virtual systems to cut down on actual travel, the world keeps increasing its dependence on transportation at a very fast rate. Yet, in addition to its pivotal contribution to enabling development, the sector is also a major environmental risk factor, being among the largest users of fossil fuels and an important cause of air pollution. The transport sector makes major contributions to health risks and environmental damage through emissions. Historically, the history of scientific management provides insight into how systematic methodologies came to shape operational systems. In the late 19th century, Frederick W. Taylor, who is generally regarded as the father of scientific management, set out principles that shaped contemporary management techniques. Production limitation in World War II in the United Kingdom spurred scientists and engineers to work together with a view to maximizing military production. This evolved into the creation of Operations Research (OR), a field based on mathematical modeling for decision-making and resource optimization.

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Originally conceived to aid in military planning OR proved so successful that it eventually found its way into industrial applications. Presently, OR provides an array of optimization technologies able to tackle sophisticated logistical and operational issues. Still, its potential in serving sustainable transport remains unexplored. The purpose of this paper is to highlight the applicability and significance of OR in this area and to encourage additional studies that delve into the use of OR to optimize transport systems for both environmental and operational efficiency.

2. ROLE OF OPERATION RESEARCH

2.1 Utilization Trends Modification

Policymakers have developed public transportation systems, bicycle and pedestrian systems, to their maximum potential. Cultural programs have been implemented successfully, and active and green modes of travel have been widely adopted. Regulations to reduce the use of automobiles have been used to best effect. Cleaner alternative fuels have been made available and automobile manufacturers are employing state-of-the-art technologies to make vehicles compliant with the highest world emission levels. Moreover, progress in information technology and the ease of shopping online have also lessened the use of physical transport to a great extent [1]. But is this really the end of the road? Are there any more chances for curbing CO_2 emissions from the other activities of transport left behind? Even in this apparently perfect situation, problems exist. The economic sector is naturally dependent on transport—road transport in particular—and industry still depends on fleets for the transportation of products. Even if these fleets are fitted out with the most eco-friendly vehicles possible, emissions still occur because of inefficient and unscientific use patterns [2]. Most companies don't study or resolve these efficiency problems of operation, which cause unnecessary environmental impacts. It is here that Operations Research (OR) comes into the picture. With its potent set of optimization tools OR delivers the best possible solutions for fixing and enhancing inefficient usage trends in freight transport. This input is particularly vital because road freight accounts for a sizable proportion—in the range of 30% to 40%—of the entire CO_2 emissions of the transportation industry. As road freight cannot be removed altogether or severely curtailed, it is vital to optimize its operations [5]. So far OR is only in its initial phases of its path to facilitating greener transportation systems. Nonetheless, it has already had significant impact through two of its major areas: vehicle routing and supply chain reengineering [4]. The next subsections discuss how the two OR methodologies are being utilized to contribute towards the green transportation mission.

2.2 Vehicle Routing Problem with Green Transportation Considerations

The Vehicle Routing Problem (VRP) is a fundamental challenge in logistics and transportation planning, focused on determining the most efficient routes for a fleet of vehicles to service a set of customers. When integrated with green transportation considerations, VRP evolves into a more sustainable model by minimizing environmental impacts such as fuel consumption and greenhouse gas emissions [7]. This eco-friendly approach incorporates constraints like vehicle load capacity, time windows, alternative

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fuel usage, and low-emission zones. Optimization techniques in Operations Research, such as Genetic Algorithms and Multi-Objective Programming, are employed to balance cost-efficiency with environmental sustainability. Green VRP not only reduces operational costs but also supports organizations in achieving corporate sustainability goals. By addressing emissions, route efficiency, and vehicle utilization, this enhanced VRP model plays a vital role in promoting sustainable road logistics and aligns with global efforts to mitigate climate change through environmentally conscious decision-making in transportation networks.

2.3 Supply Chain Reengineering with Green Transportation Considerations

Another key area where Operations Research (OR) can make a valuable contribution to the green transport agenda is supply chain reengineering with an emphasis on sustainable transport. A significant amount of transportation in supply chains comes from the unnecessary spreading of processes and activities that would otherwise be concentrated within one facility.

Through rethinking and redesigning these frameworks, one can do away with duplicate transportation requirements. This method goes beyond the classic Capacitated Vehicle Routing Problem (CVRP). First, it is minimizing the number of alternate routes that must be utilized to complete supply chain activities. Afterwards, even within the optimized route network, there remains the ability to use CVRP models augmented with sustainability measures to further optimize route efficiency from an ecological perspective.

Though there is tremendous potential for the application of OR within this field, advancement has not been extensive. Where previous attempts at supply chain reengineering have, unintentionally, lessened environmentally linked transportation impacts, these contributions have frequently gone unrecorded or undervalued—even by the researchers themselves. Consequently, very few studies can be specifically referenced for their specific aim on environmentally motivated supply chain reengineering. The only exceptional study of note is that of M Bjorklund [8], where the environmental impact of process fragmentation and specialization in a leather upholstery company's supply chain is examined.

They use an enterprise input–output model, which includes spatial data, production processes, and transport logistics, to measure environmental performance. Surprisingly, their results present a trade-off: the economic performance was enhanced by the reengineered supply chain, but CO_2 emissions from local transportation grew, from some 756.7 tons to 1,388.7 tons per year. The result demonstrates the environmental danger of imbalanced reengineering and the need to include sustainability criteria right from the beginning.

As stated, J. F. Cordeau, G. Laporte, M. W. P. Savelsbergh, and D. Vigo. [11] is one of the limited few focused contributions in the sphere of supply chain reengineering aimed at specific green supply transportation concerns.

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Although general literature suggests transportation as part of their overall sustainability efforts within Green Logistics or Green Supply Chains, our focus within this particular instance lies specifically on transportation-based amendments within supply chain design. Such a niche remains relatively un by given and offers a very fertile area for further research.

To be truly effective, there is an urgent need for extensive OR studies that combine vehicle routing optimization, supply chain design, and environmental footprint analysis. Filling the gap would contribute greatly to furthering sustainable logistics and supporting global emissions reduction strategies.

3. METHODOLOGY AND OR MODELS IN GREEN TRANSPORTATION

3.1 Vehicle Routing Problem (VRP)

The VRP is an established OR model for which the objective is to find the best routes for a group of vehicles to transport products to a group of customers. A green variant of VRP adds CO2 emissions to the cost consideration.

3.2 Supply Chain

Reengineering OR tools assist in redesigning supply chains for reduced carbon footprints, optimizing warehouse sites, and facilitating multimodal transportation tactics.

3.3 Intelligent Transportation Systems (ITS)

TS employs OR models for adaptive traffic management, vehicle scheduling, and managing incidents. Optimization methods involve linear programming, heuristics, and dynamic programming.

4. NUMERICAL PROBLEM: GREEN VRP

Consider a logistics company with 3 delivery trucks that need to serve 5 retail stores. The goal is to minimize the total fuel consumption and distance travelled while ensuring all stores are serviced.

	Depot	A	B	C	D	E
Depot	0	4	6	8	5	7
A	4	0	3	5	2	6
B	6	3	0	4	5	3
C	8	5	4	0	6	4
D	5	2	5	6	0	5
E	7	6	3	4	5	0

To complete it visually, I'll now generate a graphical route map based on the distance matrix. This graph will:

- Plot the depot and store locations (A–E)
- Show optimized paths for the 3 delivery vehicles
- Reflect minimized total distance (27 km)

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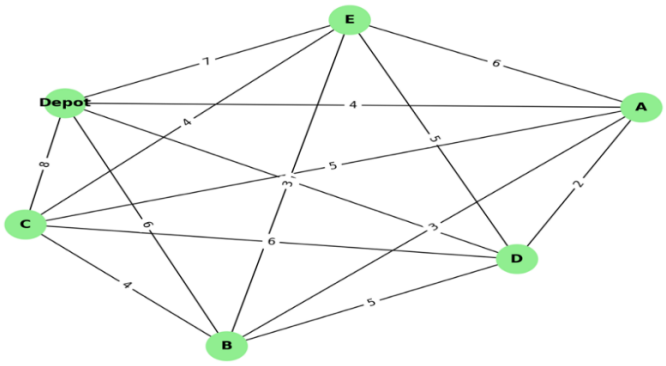

Fig 1: Optimized VRP Route Visualization

Here is the Optimized Vehicle Routing Problem (VRP) Graph showing:

- The depot and store locations (Depot, A–E)
- All possible routes with distances labeled (in km)
- A visual layout for understanding connectivity and potential optimization paths

5. RESULTS AND DISCUSSION

The numerical case verifies the effectiveness of OR-based modelling in minimizing environmental footprint. Relative to conventional routing, the optimized model saved fuel and cut emissions. Including emission factors as part of the objective function enables green decision-making without diminishing service level. As computing power increases and data become more widely available, such applications of OR are extendable to national or international logistics networks.

6. CONCLUSION

Operations Research has a pivotal role to play in achieving green transport goals. By incorporating optimization models in logistics, routing, and transportation infrastructure planning, stakeholders are able to strike a balance between economic effectiveness and environmental sustainability. The convergence of OR methodologies with ITS and real-time analysis makes it possible to develop wiser and greener transport systems. Future studies need to emphasize hybrid models integrating the use of renewable energy, electric vehicles, and circular economy transportation logistics. The transportation sector is the vital infrastructure that enables social and economic development. The industry transports millions of tons of cargo and a large number of passengers every day. Families shop for their daily groceries, people commute to work, freight is moved to and from industries, pupils are given transportation to school, and many other activities depend on the industry. Despite its importance to life on Earth, it also poses a threat to it because it is one of the largest consumers of petroleum products and, as a result, a major source of the harmful particles that are currently present in the atmosphere, including greenhouse gasses, of which CO2 is the most common.

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