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Providing a Vehicle Routing Model for the Distribution of Various Items to Optimize Operational Travel Costs: A Case Study of the Ports and Maritime Organization of Guilan Province

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Abstract

To ensure timely delivery and prevent spoilage of perishable items such as food, vegetables, flowers, ready-mixed concrete, and blood, manufacturers must select optimal delivery routes, a critical aspect of vehicle routing in operations research. This research addresses the vehicle routing problem by developing an operational plan for a fleet of homogeneous vehicles with limited capacity, dispatching products from a central warehouse to geographically dispersed customers, thereby minimizing the number of vehicles and travel costs. Given the complexity of this problem, which renders exact methods impractical for large-scale instances due to time constraints, Gams software was employed to solve the model effectively on a smaller scale. Furthermore, a case study on product distribution among customers of the Ports and Maritime Organization in Guilan Province (Bandar Anzali) demonstrates the model's practical applicability, showing that distributors can significantly reduce operating costs. Consequently, the proposed approach not only enhances supply chain efficiency but also offers substantial economic and environmental benefits by reducing fuel consumption and vehicle emissions, thereby contributing to sustainable logistics practices.

Keywords: Vehicle routing, Supply chain, Rectangular wood planks, Guilan Province Ports and Maritime Organization, Operating costs of travel

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1. Introduction

The vehicle routing problem (VRP) encompasses a broad category of optimization challenges focused on serving customers through efficient vehicle routes. In the literature, this problem is also referred to as vehicle scheduling, distribution, or simply the delivery problem. Notably, routing issues in applied contexts are not always directly tied to the physical distribution of goods and often arise periodically. For instance, applications include scheduling school buses, delivering goods between supermarkets and large retailers, distributing books and newspapers, organizing distribution tours and maintenance, and transporting refrigerated goods. These scenarios involve diverse items and vehicle types. Perishable items, such as dairy products, food, medicine, vegetables, flowers, plants, ready-mixed concrete, and blood packages, typically degrade over time from production to delivery. Consequently, the value of these items begins to decline immediately after production and continues until they reach the consumer. Thus, the revenue of producers and distributors depends significantly on the condition of these items at the time of delivery. Timely production and distribution substantially influence their income. Due to the rapid perishability of such items, producers often delay production as long as possible and prioritize swift delivery to consumers. Therefore, efficient and rapid transportation along the supply chain is a critical factor affecting vendors' revenue (Chen et al., 2009).

The vehicle routing problem for distributing diverse items represents a practical optimization challenge. Routing remains one of the most complex optimization issues, with efforts spanning over five decades to design optimal transport fleet routes to serve all customers efficiently. The VRP encompasses various constraints, including vehicle capacity, time windows, and route lengths. In essence, the VRP is a collective term for a set of optimization challenges that involve serving consumers using multiple vehicles. Typically, vehicles depart from a warehouse, serve a network of consumers, and return to the depot after completing their routes. Ultimately, the objective is to minimize the cost function while maximizing consumer satisfaction.

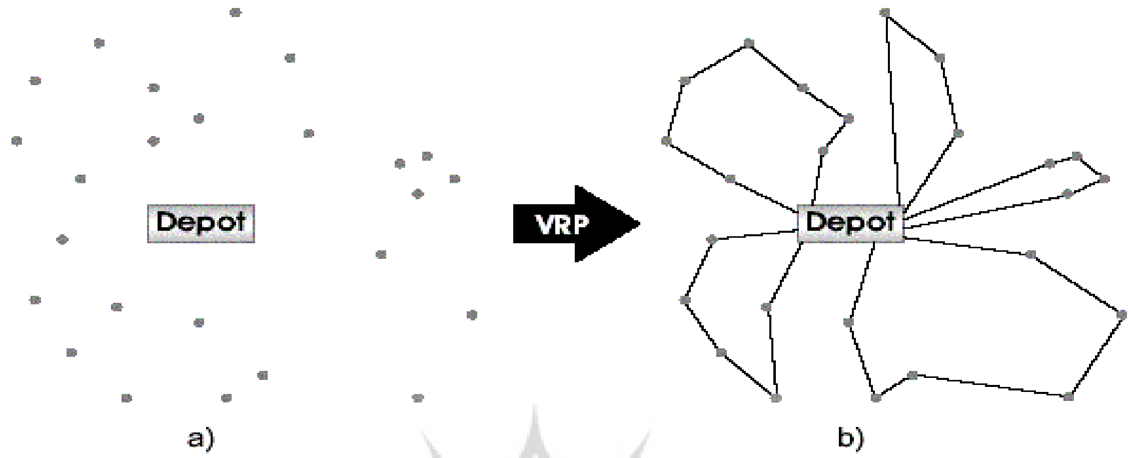

Figure 1:Problem Solving (b) - Example of a Vehicle Routing Problem (a) (Kumar & Panneerselvam, 2012)

Figure 1 provides a view of common inputs for the problem and one possible output. The vehicle routing problem for the distribution of various items is an extension of the traveling salesman problem (TSP). The TSP is a fundamental issue in transportation routing and planning. In the case of the TSP, the goal is to find the shortest route that passes through a set of cities, visiting each city exactly once before returning to the starting city. The TSP is a simplified form of the VRP, involving a single vehicle with no restrictions or specified origin, and where customers have no demand. Consequently, the VRP is significantly more complex than the TSP. The basic VRP specifies optimal routes such that each node is visited exactly once by a single transport vehicle, with routes beginning and ending at a point called the warehouse.

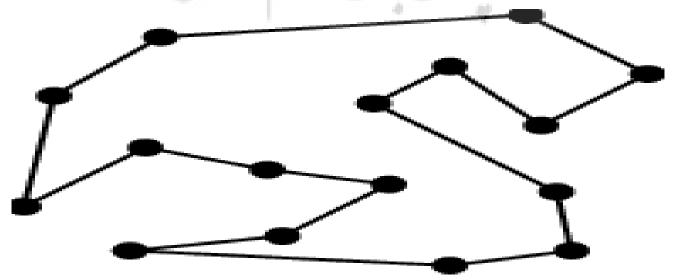

Figure 2:The Traveling Salesman Problem (Kumar & Panneerselvam, 2012)

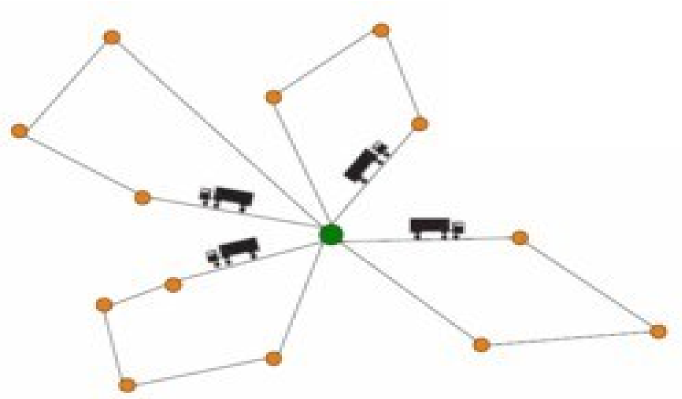

Figure 3:Vehicle Routing Problem (Kumar & Panneerselvam, 2012)

Figures 2 and 3 illustrate the TSP and VRP, respectively. The vehicle routing problem for the distribution of various items extends the traveling salesman problem (TSP). The TSP is a fundamental issue in transportation routing and planning. In the TSP, the objective is to identify the shortest route that visits a set of cities exactly once before returning to the starting city. Indeed, the TSP is a simplified version of the VRP, involving a single vehicle without restrictions or a specified origin, and where customers have no demand. Thus, the VRP is considerably more complex than the TSP. The basic VRP defines optimal routes such that each node is visited exactly once by a single transport vehicle, with routes starting and ending at the warehouse. Figures 2 and 3 illustrate the TSP and VRP, respectively. In recent decades, extensive research has addressed various routing problems and their solution methods. However, compared to the classical VRP, less attention has been devoted to the vehicle routing problem with time windows (VRPTW) for the distribution of various items. The VRPTW involves designing a set of routes for a fleet of vehicles that begin and end at the warehouse, serving a specific number of customers across different geographic areas within designated time windows. The goal is to minimize the total cost of customer service (Hashemi Amiri, 2013). A primary motivation for this research is the high cost of transporting various items from origin to destination. This study aims to minimize operating costs by proposing an efficient mathematical model.

The transportation system plays a critical role in economic development within today's industrial world by enabling the consumption of items far from their place of production. Delivering final products to customers requires transferring raw materials from suppliers to manufacturers, moving semi-finished products between factories, and ultimately distributing the final product to customers and target markets. Due to the volume of transportation activities, transportation costs constitute a significant portion of logistics costs, ranging from 40% to 70%. Consequently, the design of distribution networks has become a critical issue in supply chain and logistics management due to its substantial impact on reducing logistics costs and enhancing service quality (Ghiani et al., 2004). Furthermore, efficient transportation systems facilitate the expansion of existing markets and the creation of new ones by delivering perishable products to consumers worldwide in the shortest possible time, leveraging the competitive advantages of developing countries to produce more cost-effective products (Karaoglan et al., 2012).

2. Literature review

Federgruen et al. (1986) laid the foundational work by considering the costs of commodity shortages, spoilage, and transportation, developing an efficient mathematical model for transporting various items, and optimizing allocation. Their study demonstrated that goods produced at a central warehouse are dispatched to specified locations based on probabilistic demand. Notably, these goods, being perishable, must be used within a specific timeframe to avoid spoilage and waste. Their model accounts for two delivery scenarios: initially, each consumer's demand is met individually; subsequently, consumers are assigned to specific routes, optimizing distribution efficiency.

Building on the focus on perishable goods, Tarantilis and Kiranoudis (2001) proposed a precise and rapid solution for dairy distribution in Greece, formulating the problem as a vehicle routing model with a heterogeneous fleet. Due to the model's complexity, no suitable solution had been identified at the time. To address this, they developed a threshold-based algorithm to meet organizational needs, aiming to enhance efficiency and productivity. In a subsequent study, Tarantilis and Kiranoudis (2002) extended this approach by modeling the distribution of meat products between warehouses and distribution centers in Greece as a multi-depot vehicle routing problem. By employing a metaheuristic random search method, they demonstrated significant economic savings, highlighting the practical applicability of their solution.

Similarly, Hsu and Hung (2003) addressed time-constrained vehicle routing for frozen food distribution. Recognizing high consumer demand, they proposed loading goods in excess of demand to ensure availability. Their model specifies constraints such as vehicle numbers, carrying capacity, travel time, and associated routes, offering a practical framework for managing time-sensitive deliveries.

In a related vein, Azi et al. (2004) explored a vehicle routing problem with time windows, where a single vehicle is assigned multiple routes within a day. This model is particularly relevant for delivering perishable goods, such as food, to urban centers, where short routes enable multiple daily deliveries, enhancing operational efficiency.

Further advancing the field, Belenguer et al. (2005) formulated the distribution of protein products for a Spanish organization as a vehicle routing problem with time window constraints. They developed algorithms implemented as a computer-based support system, facilitating effective product distribution and operational management.

In contrast, Ambrosino and Sciomachen (2006) modeled food distribution for an Italian organization as a capacitated vehicle routing problem, focusing on distributing two types of goods across a national network. They proposed a two-stage approach: first, segmenting consumers and identifying vehicle routes; second, optimizing operating costs by reassigning consumers among routes. This method underscores the importance of strategic route planning in large-scale distribution.

Shifting focus to the integration of production and distribution, Zaeri et al. (2007) investigated newspaper production and distribution, emphasizing the critical linkage between these operations for perishable goods. They introduced an innovative method using cluster-to-cluster analysis and the traveling salesman model to determine demand points and allocate vehicle routes effectively, enhancing distribution efficiency.

Similarly, Hsu et al. (2007) tackled the vehicle routing problem with time constraints for perishable item delivery, proposing a mathematical model to optimize routes, vehicle capacity, and departure times. Their model minimizes fixed vehicle costs, freight costs, energy consumption, and time-window penalties. Moreover, they examined variables such as vehicle travel times, traffic impacts, temperature variations, and objective function changes, introducing an innovative algorithm, TONNH, to solve the model efficiently.

Extending this focus on time constraints, Budchar and Sethanan (2009) presented an innovative algorithm for vehicle routing in perishable item distribution, considering time window constraints. Their model minimizes maintenance costs for perishable goods, fuel costs, and late-delivery penalties. They identified key factors affecting the objective function, including the number of distribution centers, their distances, and the volume of items transported. Consequently, their results offer practical solutions for minimizing operating costs and ensuring timely deliveries.

In a complementary approach, Chen et al. (2010) developed a nonlinear programming model for the vehicle routing problem, incorporating probabilistic consumer demand and a defined spoilage rate post-production. As supplier revenue depends on spoilage levels, their model maximizes expected benefits. After solving the model, they determined optimal production quantities, start times, and vehicle routes using an innovative algorithm based on the Nelder-Mead method, which proved highly accurate and efficient for time-constrained routing.

Likewise, Gong and Fu (2010) proposed a multi-objective model for vehicle routing in perishable food distribution in large cities, accounting for time constraints. Their model incorporated costs such as production, fixed vehicle costs, food spoilage, and time-window penalties, providing a comprehensive framework for urban logistics.

In a nuanced variation, Azi et al. (2010) examined a vehicle routing model where a vehicle serves multiple routes daily, with not all consumers receiving service. Consumer selection is based on revenue minus travel costs, and they employed an innovative algorithm to solve the model, optimizing operational decisions.

Furthermore, Farahani et al. (2012) demonstrated that minimizing the time between production and delivery improves perishable product quality. They adopted an integrated approach combining production and distribution planning, formulated as an integer linear programming model to ensure minimum quality standards. Their innovative algorithm divides production into two stages, integrating it with distribution to reduce model complexity and enable timely solutions.

Finally, Barreto et al. (2012) addressed vehicle routing for frozen item distribution, focusing on maintaining quality and preventing spoilage. Their work underscores the importance of tailored routing strategies for temperature-sensitive goods, contributing to the broader discourse on perishable item logistics.

3. Problem definition and mathematical model

The vehicle routing problem (VRP) is represented by a graph G = (V, A), where the set V = {V_0 , V_1 , ..., V□} denotes a collection of nodes, and A = {(V□, V□) | V□, V□ ∈ V, i ≠ j} represents a set of arcs connecting these nodes. The node V_0 corresponds to the warehouse, while nodes V_1 to V□ represent consumers. Associated with each arc (i, j), the parameter C□,□ indicates the distance traveled or the time and cost incurred during travel. For each consumer V□, a delivery demand d□ ≥ 0 and a pickup demand P□ are defined. The decision variable x□,□,□ equals 1 if vehicle k traverses the arc (i, j), and 0 otherwise, where k denotes the number of vehicles used (Solomon, 1987).

Building on this framework, the model proposed in this research for the vehicle routing problem involving the distribution of diverse items is an NP-hard variant of VRP models. This model incorporates three decision variables, eleven constraints, four indices, and eight parameters, which are fully described below. The main model of this study is presented as follows (Authors).

$$\text{Minimize} \quad \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{j \neq i, k=1}^{K} c_{ij} x_{ijk}$$

subject to:

$$\sum_{k=1}^{K} \sum_{j=1}^{N} x_{ijk} \leq K, \quad \text{for } i = 0 \tag{1}$$

$$\sum_{j=1}^{N} x_{ijk} = 1 \quad \text{for } i = 0 \text{ and } k \in \{1, \cdots, K\} \tag{2}$$

$$\sum_{J=1}^{N} x_{jik} = 1 \quad \text{for } i = 0 \text{ and } k \in \{1, \cdots, K\} \tag{3}$$

$$\sum_{k=1}^{K}\sum_{j=0,j\neq i}^{N} x_{ijk} = 1, \quad \text{for } i \in \{1,\cdots,N\} \tag{4}$$

$$\sum_{k=1}^{K}\sum_{i=0,i\neq j}^{N} x_{ijk} = 1, \quad \text{for } j \in \{1,\cdots,N\} \tag{5}$$

$$\sum_{i=1}^{N} m_i \sum_{j=0,j\neq i}^{N} x_{ijk} \leq q_k, \quad \text{for } k \in \{1,\cdots,K\} \tag{6}$$

$$\sum_{i=0}^{N}\sum_{j=0,j\neq i}^{N} x_{ijk}\left(t_{ij} + f_i + w_i\right) \leq r_k, \quad \text{for } k \in \{1,\cdots,K\} \tag{7}$$

$$T_0 = w_0 = f_0 = 0 \tag{8}$$

$$\sum_{k=1}^{K}\sum_{i=0,i\neq j}^{N} x_{ijk}\left(T_i + t_{ij} + f_i + w_i\right) \leq T_j, \quad \text{for } i \in \{1,\cdots,K\} \tag{9}$$

$$e_i \leq \left(T_i + w_i\right) \leq l_i \quad \text{for } i \in \{1,\cdots,N\} \tag{10}$$

Sets

i: Starting city

j: Destination city

k: Total number of vehicles

N: Total number of customers

Principal Decision Variables

T_i: Arrival time at node i

W_i: Wait time at node i

$X_{ijk} \in \{0,1\}$, 0 if there is no arc from node i to node j, and 1 otherwise

Parameters

C_{ij}: Cost incurred on arc from node i to j

t_{ij}: Travel time between node i and j

m_i: Demand at node i

q_k: Capacity of vehicle k

e_i: Earliest arrival time at node i

l_i: Latest arrival time at node i

f_i: Service time at node i

r_k: Maximum route time allowed for vehicle k

The objective function and constraints of the model are described as follows:

The objective function minimizes the operating costs of transportation routes. Constraint set 1 ensures that the number of routes equals K by selecting at most K outgoing arcs from the depot (i=0).

Constraint set 2 guarantees that exactly one outgoing arc from the depot is selected for each vehicle. Similarly, constraint set 3 ensures that exactly one incoming arc to the depot (i=0) is selected for each vehicle. Together, these constraints (sets 2 and 3) ensure that each vehicle completes a single, continuous route.

Furthermore, constraint set 4 ensures that exactly one arc emanates from each node i for each vehicle. Likewise, constraint set 5 guarantees that exactly one arc enters each node j for each vehicle. Collectively, these constraints (sets 4 and 5) ensure that each vehicle visits each node exactly once.

Constraint set 6 ensures that the total demand (load) assigned to each vehicle does not exceed its capacity. Similarly, constraint set 7 guarantees that the total travel time for each vehicle's route is less than or equal to the maximum allocated route time.

Moreover, constraint set 8 sets the arrival time, waiting time, and service time of each vehicle at the depot to zero. Constraint set 9 ensures that the arrival time of each vehicle at node j is less than or equal to the specified arrival time for that node. Additionally, constraint set 10 guarantees that the sum of the arrival time and waiting time of each vehicle at each node i falls within the earliest and latest arrival times for that node. Collectively, constraint sets 8–10 define the time window requirements.

4. Case study

By examining the transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali), the necessary information for developing the vehicle routing model was obtained, as detailed below.

The data, collected over 10 working days from the transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali), served as the basis for constructing the model. Specifically, this information was used to develop a vehicle routing model as an illustrative example. The required data are presented as follows.

Table 1:*Model Sets Based on the Case Study*

i	$i \in \{1,2,3,4,5,6\}$
j	$j \in \{1,2,3,4,5,6\}$
k	$k \in \{1,2,3,4,5,6\}$
N	6

Table 2:*Demand for Rectangular Wooden Planks in City i*

i	1	2	3	4	5	6
mi	840	840	960	1200	840	1080

The demands in Table 2 represent the number of rectangular wooden planks required for each city.

Figure 4:View of Rectangular Wooden Planks (Authors)

Table 3:*Vehicle Capacity k for Rectangular Wooden Planks*

k	1	2	3	4	5	6
qk	850	850	960	1320	850	1320

The vehicle capacities in Table 3 are specified for transporting rectangular wooden planks.

Table 4:*Times of first arrival in the city i*

i	1	2	3	4	5	6
ei (min)	135	195	285	405	225	435

Table 5:*Last times of arrival in the city i*

i		1	2	3	4	5	6
li (min)		210	285	390	515	320	545

Table 6:*Duration of service in the city i*

i	1	2	3	4	5	6
fi (min)	55	70	80	90	65	85

Table 7:*Maximum time allowed for travel by vehicle k*

k	1	2	3	4	5	6
rk (min)	170	240	280	410	275	495

Table 8: *Travel time between city i and city j*

T(i , j)	1	2	3	4	5	6
1	110	180	220	350	215	435

Table 9: *Cost of routes traveled between city i and city j*

C(i , j)	1	2	3	4	5	6
1	15	19	21.5	22.5	25	20.5

Travel times in Table 8 are measured in minutes, and costs in Table 9 are in dollars.

In addition to the numerical data presented in the tables, further information required for developing the model is outlined as follows:

1. The data represent a random sample collected over 10 working days from the transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali).
2. The transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali) distributes various goods across Iran. For this study, rectangular wooden planks are used as an illustrative example.
3. The vehicles, including trucks, 10-wheel trailers, and 18-wheel trailers, each have specific capacities. The vehicle type is determined based on customer demand.
4. The Ports and Maritime Organization of Guilan Province (Bandar Anzali) collaborates with six private companies specializing in loading and unloading. For this study, the Iran Ports Company was selected as the basis for developing the vehicle routing model, using its operational data.
5. The transportation system delivers goods to numerous cities in Iran. This study focuses on six cities requesting rectangular wooden planks: Talesh (1), Astara (2), Qazvin (3), Tehran (4), Shahsavar (5), and Sari (6). The model sets are ordered according to these cities, as detailed in Tables 10 and 11.

Table 10: Set i is related to the starting city

i	1,2,3,4,5,6
Starting city	Bandar Anzali Port Organization

Table 11: *Destination cities*

j	1	2	3	4	5	6
Destination cities	Talesh	Astara	Qazvin	Tehran	Shahsavar	Sari

6. The data used for the model constitute a random sample of the transportation system's operations, with variables, items, and the selected company chosen randomly.

5. Computational results

Based on the model's solution using GAMS software, the values of each decision variable were determined, minimizing the operating costs of vehicle routes to the specified cities.

Table 12: *Travel expenses before and after solving the model*

Cities	Talesh	Astara	Qazvin	Tehran	Shahsavar	Sari	Total Costs
Total travel expenses before solving the model	15	19	21.5	22.5	25	20.5	123.5
Total travel expenses after solving the model	11.5	16	19	20.5	24	19	110
The difference between the two costs	3.5	3	2.5	2	1	1.5	13.5

Costs are measured in dollars. As shown in Table 12, the model reduced operational costs, with the highest percentage reduction observed for Talesh and the lowest for Shahsavar.

The graph of the percentage reduction of travel operating expenses is given in Figure 5.

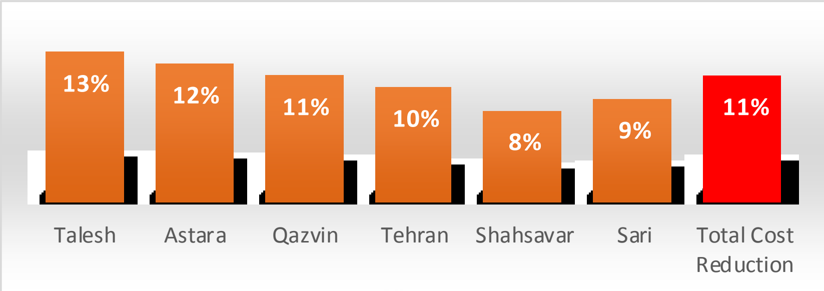

Figure 5:Percentage reduction chart of travel operating expenses (Author)

The results were analyzed in Excel software as a statistical chart, confirming that the operating costs for the designated routes were minimized.

6. Conclusion

To demonstrate the application of the vehicle routing problem using data from the transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali), a mathematical model for distributing various items was developed. This model was implemented in the GAMS software environment, and the results of the optimization were presented.

The objective of this study was to develop an efficient mathematical model to minimize vehicle travel costs. To this end, a vehicle routing model was formulated, and a case study of the transportation system of the Ports and Maritime Organization of Guilan Province (Bandar Anzali) provided a real-world example. This case study illustrated the model’s practical applicability, demonstrating its potential to minimize organizational costs and enhance performance and efficiency across various domains through the use of tailored mathematical models..

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