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MULTICRITERIA MATHEMATICAL MODEL FOR OPTIMIZING INTRA-PLANT TRANSPORTATION ROUTES CONSIDERING ERGONOMIC AND ENVIRONMENTAL FACTORS

БАГАТОКРИТЕРІАЛЬНА МАТЕМАТИЧНА МОДЕЛЬ ОПТИМІЗАЦІЇ МАРШРУТІВ ВНУТРІШНЬОЗАВОДСЬКИХ ПЕРЕВЕЗЕНЬ З УРАХУВАННЯМ ЕРГОНОМІЧНИХ ТА ЕКОЛОГІЧНИХ ФАКТОРІВ

The article proposes a multi-criteria mathematical model for optimizing in-plant road transport routes, taking into account time, ergonomic, and environmental factors. In-plant transport flows are an essential component of production and logistics systems, and improving their efficiency directly affects energy performance, production sustainability, and working conditions. The developed model is based on minimizing three groups of criteria: transportation and idle time, energy consumption and emissions, as well as ergonomic indicators related to driver workload. The optimization problem can be solved using the weighted coefficients method and heuristic algorithms. The proposed approach allows for reducing total resource consumption, improving occupational safety and comfort, and supporting sustainable development principles at the enterprise level. The results obtained can be applied to implement intelligent transport systems within industrial facilities.

Keywords*: in-plant transport, multi-criteria optimization, routing, intelligent transport systems (ITS), ergonomics, sustainable development, environmental efficiency, mathematical modeling.*

У статті розроблено багатокритеріальну математичну модель, спрямовану на вдосконалення маршрутів внутрішньозаводських автомобільних перевезень із комплексним урахуванням часових, ергономічних та екологічних чинників. Внутрішньозаводські транспортні процеси визначаються як одна з ключових підсистем виробничо-логістичної структури підприємства, оскільки саме від їхньої організації залежить ритмічність технологічного циклу, рівень енергоспоживання, ефективність використання техніки та комфорт працівників. Підвищення результативності таких перевезень безпосередньо впливає на стійкість виробництва, зниження витрат і підвищення конкурентоспроможності промислових підприємств.

Створена модель базується на одночасній мінімізації трьох груп критеріїв. До першої належать часові показники — тривалість рейсів, простої та коефіцієнти використання робочого часу транспортних засобів. Друга група охоплює енергетичні та екологічні параметри, *зокрема витрати енергії, рівень шкідливих викидів і показники енергоефективності. Третя група об'єднує ергономічні критерії, що характеризують фізичне та психофізіологічне навантаження на водіїв, комфортність умов праці та дотримання вимог безпеки. Такий підхід дозволяє забезпечити збалансованість між технічними, економічними й гуманітарними аспектами організації транспортного процесу.*

Для розв'язання задачі оптимізації можуть застосовуватись метод зважених коефіцієнтів, еволюційні та евристичні алгоритми, які забезпечують пошук компромісних рішень у системах із великою кількістю взаємопов'язаних параметрів. Результати дослідження можуть бути використані для вдосконалення транспортних процесів у різних видах виробництва — від металургійного до машинобудівного — де внутрішні перевезення мають складну структуру маршрутів і значний вплив на загальну продуктивність.

Практична цінність розробленої моделі полягає у можливості її впровадження в інтелектуальні транспортні системи підприємств, що забезпечує скорочення енергетичних витрат, підвищення безпеки руху, покращення умов праці персоналу та сприяє реалізації концепції сталого розвитку у промисловому секторі.

Ключові слова: *внутрішньозаводські перевезення, багатокритеріальна оптимізація, маршрутизація, інтелектуальні транспортні системи, ергономіка, сталий розвиток, екологічна ефективність, математичне моделювання.*

Problem's Formulation

Internal plant transportation represents a key element of the transport and production system at any industrial facility. It ensures the movement of raw materials, semi-finished products, and finished goods between different technological units, thereby directly affecting overall production efficiency and process performance. The effectiveness of these internal transport operations has a notable influence on operating costs, production cycle durations, and the ability to meet planned schedules.

Traditional optimization techniques for in-plant transport have largely focused on minimizing travel distances or transit times. Typically, these methods employ conventional routing strategies, graph-based models, or simple heuristic approaches. However, with the growing emphasis on sustainable development and the adoption of Intelligent Transport Systems (ITS), there is a need for a more integrated optimization approach. Such an approach should simultaneously address operational efficiency, ergonomic factors, and environmental impacts to enhance productivity while protecting worker health and reducing ecological burdens.

Ergonomic optimization targets the safety and comfort of vehicle operators, seeking to minimize physical stress, fatigue, and mental workload. This involves careful route planning, scheduling of rest periods, ergonomic vehicle design, and equitable distribution of work tasks. Environmental considerations aim to decrease energy consumption, reduce emissions, and limit noise levels within the plant. The incorporation of these aspects is essential for aligning in-plant transportation systems with principles of sustainable and responsible industrial operations.

The purpose of this study is to develop a multi-criteria mathematical model for the comprehensive optimization of internal transport routes, integrating technical, ergonomic, and environmental factors. This model is intended as a decision-support framework, assisting managers in achieving a balanced approach that maximizes operational efficiency, safeguards employee well-being, and promotes environmental sustainability, ultimately contributing to the establishment of smarter, safer, and greener in-plant transport systems.

Analysis of recent research and publications

Optimizing transport routes is a fundamental challenge in operations research, attracting attention due to its theoretical significance and practical applications. Traditional approaches, such as the classic Traveling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP), have primarily concentrated on minimizing total travel distances or journey durations [1—3]. However, in industrial settings—especially within internal plant logistics—these conventional models often need significant adaptation. To address this, modified VRP frameworks have been proposed, incorporating essential operational constraints such as vehicle load limits, sequencing of technological operations, idle times, and queue dynamics at workstations [4—6].

Recently, research has increasingly focused on incorporating human factors into transport optimization. Studies underscore the importance of accounting for driver fatigue, mandatory rest periods, and psychological stress, given their direct influence on both safety and operational performance [7, 8]. Simultaneously, there is growing attention to the environmental consequences of in-plant logistics. Modern approaches integrate ecological metrics, aligning route optimization with sustainable development objectives and carbon footprint reduction [9, 10].

Despite these developments, the literature still shows a gap regarding comprehensive models that simultaneously consider ergonomic, temporal, and environmental aspects. In particular, internal plant transportation—a key element of industrial production—lacks integrated frameworks that merge human factors, operational efficiency, and ecological sustainability into a single optimization strategy. This underscores the need for further research to develop holistic solutions capable of enhancing productivity while promoting environmentally responsible industrial logistics.

Formulation of research purpose

The main goal of this study is to develop an integrated mathematical model that simultaneously reduces total time expenditures and energy consumption, while improving ergonomic conditions for drivers engaged in in-plant transport operations. The model provides a structured framework for planning and managing internal logistics processes within industrial facilities. By incorporating temporal, energetic, and human-factor parameters, the approach aims not only to enhance operational efficiency but also to promote employee well-being and safety, supporting a more sustainable and robust production system. Additionally, the model is designed as a decision-support tool for industrial managers, facilitating informed planning, optimized vehicle deployment, and the mitigation of idle periods and operational bottlenecks. Ultimately, this research seeks to advance industrial transport management practices by integrating productivity, ergonomics, and environmental responsibility into a single cohesive optimization framework.

Presenting main material

Problem statement

Internal transportation of technological cargoes constitutes a critical element of the transport and production system within any industrial facility. It enables the organized transfer of raw materials, semi-finished products, and finished goods across various technological units, directly affecting production efficiency, workflow continuity, and operational safety. Effective in-plant transport not only ensures adherence to production schedules but also promotes the efficient utilization of resources, including energy, labor, and equipment.

The primary aim of the proposed model is to minimize the total costs associated with internal transport operations. This goal is achieved by concurrently considering multiple interconnected factors: temporal parameters, such as transit and idle times; environmental impacts, including energy usage and emissions; and ergonomic requirements, ensuring safe and comfortable working conditions for drivers and operational staff. By combining these criteria into a single, cohesive framework, the model seeks to improve the efficiency, sustainability, and human-centricity of in-plant transportation, thereby facilitating better-informed decision-making and strategic planning in industrial logistics management.

Let us define the set of transport points:

$$I = \{1,2,\dots,N\}, \quad (1)$$

and the set of vehicles:

$$J = \{1,2,\dots,M\}. \quad (2)$$

Each vehicle $j \in J$ has the following technical parameters: Q_i — load capacity, t; v_i —average speed, km/h; n_i — energy efficiency coefficient; f_i — ergonomic factor (fatigue or discomfort index).

For each pair of transport points $(i,k) \in I \times I$ the following parameters are given: d_{ik} — distance between points, km; t_{ikj} — travel time for vehicle j; e_{ikj} — energy or fuel consumption; s_i, s_j — loading and unloading times, respectively.

Model variables

A binary variable is introduced:

$$x_{ikj} = \begin{cases} 1, & \text{if vehicle } j \text{ performs transport from point } i \text{ to } k \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Additional variables: T_j — total operating time of j; E_j — total energy consumption; F_j — generalized ergonomic workload indicator for the driver.

Objective function

The model aims to minimize the integrated criterion:

$$\min F = w_1 F_t + w_2 F_e + w_3 + F_f, \quad (4)$$

where $F_t = \sum_i \sum_k \sum_j t_{ikj} x_{ikj}$ — total time costs; $F_e = \sum_i \sum_k \sum_j e_{ikj} x_{ikj}$ — total energy or fuel costs; $F_f = \sum_j T_J$ — ergonomic component (driver workload); w_1, w_2, w_3 — weighting coefficients determining the relative importance of each ($w_1 + w_2 + w_3 = 1$).

System of constraints

1. Each point is serviced exactly once:

$$\sum_{j=1}^{M} \sum_{k=1,k\neq i}^{N} x_{ikj} = 1, \qquad \forall \in I. \quad (5)$$

2. Vehicle load capacity constraint:

$$q_i \leq Q_j, \qquad \forall (i,k,j) \; : \; x_{ikj} = 1, \quad (6)$$

where $q_i -$ is the cargo mass at point i.

3. Loading-unloading balance:

$$\sum_{i=1}^{N} q_i = \sum_{k=1}^{N} q_k, \quad (7)$$

where $q_i -$ is the cargo loaded at point i; q_k — cargo unloaded at k.

4. Driver working time constraint:

$$T_j = \sum_i \sum_k t_{ikj} x_{ikj} + \sum_i s_i \leq T_j^{max}, \qquad \forall j \in J, \quad (8)$$

where T_j^{max} — allowable working time according to ergonomic standards.

5. Route connectivity constraint:

$$\sum_{k=1,k\neq i}^{N} x_{ikj} = \sum_{k=1,k\neq i}^{N} x_{kij}, \qquad \forall i, j. \quad (9)$$

6. Non-negativity and binary constraints:

$$x_{ikj} \in \{0,1\}, \qquad T_j, E_j, F_j \geq 0. \quad (10)$$

Evaluation of ergonomic factors

The ergonomic index f_j is defined as a function of work duration, noise level, vibration, and microclimatic conditions in the cabin:

$$f_j = \alpha_1 T_j + \alpha_2 L_j + \alpha_3 V_j + \alpha_4 C_j, \quad (11)$$

where L_j — average noise level, dB; V_j — vibration amplitude, m/s^2; C_j — microclimate coefficient (temperature deviation); $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ — weighting coefficients for each factor.

Environmental component

Energy consumption e_{ikj} is determined by:

$$e_{ikj} = \frac{d_{ik}}{v_j \eta_j} \cdot (P_j + P_{\text{дод}}), \quad (12)$$

where P_j — engine power; $P_{\text{дод}}$ — additional power consumption of auxiliary systems.

Carbon dioxide emissions are calculated as:

$$\mathrm{CO}_{2,ikj} = r \cdot e_{ikj}, \quad (13)$$

where r — specific emission factor (g CO_2 / kWh).

Solution method

The weighted sum method can be used to solve the model, reducing the multi-objective problem to a single-objective one:

$$\min F = w_1 F_t + w_2 F_e + w_3 F_f. \quad (14)$$

To obtain a set of Pareto-optimal solutions, the following methods can be applied: Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Ant Colony Optimization (ACO).

For medium-sized problems ($N < 20$) linear integer programming can be applied using environments such as MATLAB, LINGO, or Python (PuLP).

Structural Framework of the Multi-Criteria Intra-Plant Transport Optimization Model

Figure 1 depicts the structural framework of a multi-criteria model for optimizing intra-factory transport operations. The diagram highlights the primary components of the system, including transportation points, the fleet of vehicles, and operational constraints such as load limits, drivers' working hours, and equitable workload distribution. It underscores the model's purpose of enhancing overall performance by evaluating multiple efficiency criteria simultaneously. The figure also points to potential optimization approaches suitable for solving this type of problem, such as genetic algorithms, particle swarm optimization, and ant colony optimization, illustrating the model's adaptability for applying advanced computational methods in practical transport management.

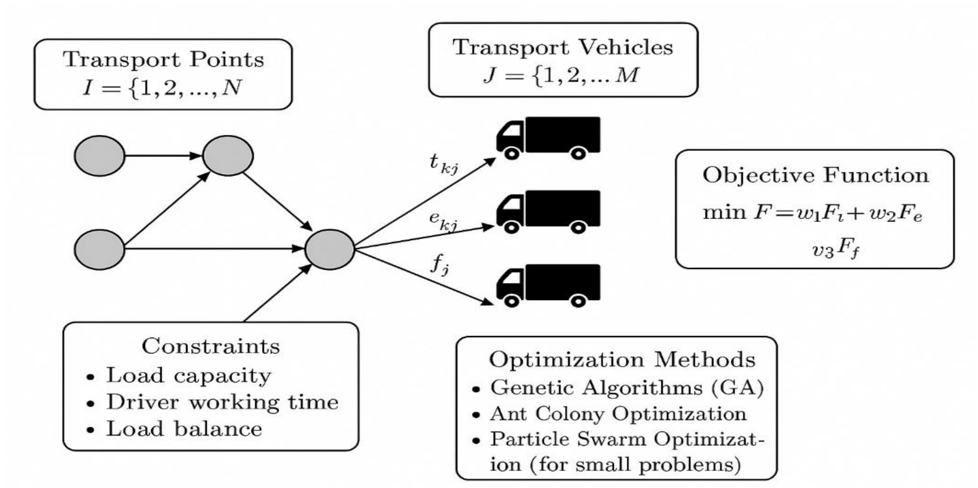

Fig. 1. Structural diagram of the multi-criteria in-plant transport optimization model

Figure 1 Structural diagram of the multi-criteria intra-factory transport optimization model, showing transportation points, vehicles, operational constraints, and examples of applicable optimization methods such as genetic algorithms, particle swarm optimization, and ant colony optimization.

Conclusions

A holistic multi-criteria mathematical model has been developed to optimize in-plant transportation processes by integrating temporal, energy, and ergonomic considerations within a single decision-making framework. This advanced model enables the simultaneous reduction of transport durations and energy usage while alleviating the physical and psychophysiological burden on drivers, thus harmonizing operational efficiency with worker well-being. By explicitly incorporating an ergonomic indicator, the framework formalizes the human factor, enhancing occupational safety and supporting sustainable workforce management.

The methodology combines multi-objective optimization techniques with global search algorithms, ensuring adaptability and robustness under varying production scenarios and operational conditions. Its design allows scalable deployment within enterprise-level intelligent transport systems, promoting automation, reducing idle times, and optimizing vehicle utilization. Furthermore, the model provides a data-driven basis for managerial decision-making, facilitating strategic planning, real-time operational adjustments, and alignment with environmental sustainability objectives. Overall, this integrated approach advances the synergy of productivity, ergonomics, and ecological responsibility in modern industrial transport systems.

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