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Optimizing cargo space utilization in road transport with non time-dependent constraints

Optymalizacja wykorzystania przestrzeni ładunkowej w transporcie drogowym z uwzględnieniem ograniczeń niezależnych od czasu

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Abstract

This article evaluates the effectiveness of a two-stage optimization algorithm supporting cargo space utilization in international road transport under non-time-dependent physical constraints. The algorithm maximizes freight value by consolidating compatible additional loads within weight and volume limits and then determines the optimal delivery sequence. A theoretical–empirical approach was applied using a case study of a transport operation from Madrid (Spain) to Warsaw (Poland). The methodology combines a multidimensional Knapsack Problem to select feasible loads based on a maximum payload of 24 tons and a capacity of 33 Euro-pallets with the nearest neighbour algorithm (Travelling Salesperson Problem, TSP) to identify the shortest route. Economic performance was assessed using the freight-to-distance ratio (EUR/km). The results demonstrate that the proposed approach prevents overloading and cubing out while achieving 97% volume utilization and 64.5% weight utilization. The optimal scenario increased profitability to 1.22 EUR/km, representing a 22% improvement over the baseline value of 1.00 EUR/km. The findings confirm that integrating Knapsack and TSP algorithms under structural vehicle constraints can improve transport profitability and resource efficiency without fleet expansion.

Keywords: road transport, cargo space optimization, transport management, sustainable logistics

Streszczenie

Celem badania jest ocena skuteczności dwuetapowego algorytmu optymalizacyjnego wspomagającego planowanie przestrzeni ładunkowej w międzynarodowym transporcie drogowym z uwzględnieniem fizycznych ograniczeń niezależnych od czasu. Algorytm maksymalizuje wartość przewożonego frachtu poprzez konsolidację kompatybilnych ładunków dodatkowych w granicach limitów masy i objętości oraz wyznacza optymalną kolejność dostaw. Zastosowano podejście teoretyczno-empiryczne oparte na studium przypadku przewozu z Madrytu (Hiszpania) do Warszawy (Polska). Metodologia łączy wielowymiarowy problem plecakowy (Knapsack Problem), służący do wyboru dopuszczalnych ładunków przy maksymalnej ładowności 24 ton i pojemności 33 europalet, z algorytmem najbliższego sąsiada (problem komiwojażera – TSP) wyznaczającym najkrótszą trasę. Efektywność ekonomiczną oceniono za pomocą wskaźnika EUR/km. Wyniki wykazały, że algorytm skutecznie eliminuje ryzyko przeciążenia i zjawiska „cubing out", osiągając wykorzystanie 97% objętości oraz 64,5% ładowności. Optymalny wariant zwiększył rentowność do 1,22 EUR/km, czyli o 22% względem wartości bazowej 1,00 EUR/km. Uzyskane wyniki potwierdzają, że integracja algorytmów problemu plecakowego i TSP zwiększa rentowność transportu oraz efektywność wykorzystania zasobów bez konieczności rozbudowy floty.

Słowa kluczowe: transport drogowy, optymalizacja przestrzeni ładunkowej, zarządzania transportem, logistyka zrównoważona

Introduction

Road freight transport remains the indispensable backbone of European supply chains, yet the sector operates under unprecedented economic and environmental pressures. Fluctuating fuel costs, chronic driver shortages, and tightening regulatory frameworks aimed at reducing greenhouse gas emissions – such as the European Green Deal – force transport enterprises to seek internal operational reserves (Piecyk, McKinnon, 2010; The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2019) 640 final, 2019). Maximizing the utilization of existing transport assets has emerged as one of the most effective strategies to protect profit margins and meet sustainability targets without requiring capital-intensive fleet expansions (Fajczak-Kowalska, Tokarski, 2023).

While temporal requirements often dictate the rhythm of modern supply chains, the ultimate limits of transport efficiency are rigidly defined by physical and spatial boundaries (McKinnon et al., 2015). In road freight operations, ignoring non time-dependent constraints – such as weight limits, volumetric capacity, cargo geometry, and stackability – frequently leads to the phenomenon of "cubing out" (running out of space before reaching the weight limit) or overloading.

In everyday operational practice, particularly within the Less-than-Truckload (LTL) and partial load segments, dispatchers frequently rely on intuition, manual calculations, and heuristic experience to match base loads with supplementary freight. However, human-driven consolidation processes struggle to process multidimensional variables efficiently (Crainic, Laporte, 1997). This often results in suboptimal vehicle fill rates, unutilized cargo space, and missed revenue opportunities, inadvertently contributing to the high percentage of empty or partially empty miles in European transport networks (Savy, Burnham, 2013).

The optimization of cargo space without the strict pressure of delivery time windows shifts the operational focus from scheduling to advanced multi-dimensional space management, which has become a critical element in the sustainable development of modern manufacturing and logistics enterprises (Tokarski, Łuczak, 2023). In this context, decision-makers face a variation of the classic Knapsack Problem, where the objective is to maximize the total freight value by consolidating compatible additional loads, strictly within the legal and technical limits of the vehicle (Martello, Toth, 1990; Crainic, 2000).

This paper addresses the challenge of maximizing the utilization of standard heavy goods vehicles (HGV) by applying algorithmic selection of partial loads based on weight, Euro-pallet (EP) volume, and subsequent route sequencing to minimize the total distance. By combining a multi-dimensional Knapsack algorithm with the Travelling Salesperson Problem (TSP), this study provides a practical, data-driven framework that bridges the gap between theoretical operations research and daily dispatching tasks, proving that relatively simple mathematical models can yield significant economic and environmental dividends.

Methodology

The methodological foundations, including the basic optimization model and the research environment, have been thoroughly presented in the first part of this study (Fudali, 2026). Therefore, this section directly introduces the extension of the model to account for non time-dependent constraints, such as vehicle weight capacity and spatial dimensions.

The optimization process in this phase is divided into two distinct algorithms:

1. **The Selection Phase (Multi-dimensional Knapsack Problem):** The algorithm evaluates a pool of potential partial loads. The objective is to maximize the total financial value of the cargo (c_i), subject to the absolute constraints of the vehicle's maximum payload ($W_{\max}$) and volumetric capacity ($Q_{\max}$). For a standard European semi-trailer, the constraints are defined as $W_{\max} = 24$ tons and $Q_{\max} = 33$ EP. The selection is mathematically governed by the following conditions:

$$\sum_{i=1}^{n} c_i x_i \rightarrow \max \tag{1}$$

$$\sum_{i=1}^{n} w_i x_i \leq W\max \tag{2}$$

$$\sum_{i=1}^{n} q_i x_i \leq Q \max \tag{3}$$

(where w_i is the weight, q_i is the volume in EP, and x_i $\{0,1\}$ is the binary decision variable).

2. **The Routing Phase (Travelling Salesperson Problem – TSP):** Once the optimal set of loads is selected, the algorithm determines the shortest possible sequence connecting the loading and unloading points (Dantzig, Fulkerson, Johnson, 1954). Because time windows are ignored in this variant, the routing sequence is heavily influenced by physical cargo handling constraints, particularly the LIFO (Last In, First Out) rule, to minimize the need to unload and reload cargo during transit.

The integration of these two phases creates a comprehensive decision-support framework. While the selection phase guarantees that the vehicle's structural and legal boundaries are not breached, the routing phase ensures the operational feasibility of the transport task. Ultimately, the effectiveness of this combined approach is assessed using the freight-to-distance profitability indicator (EUR/km), which serves as the primary metric for comparing the optimized consolidation against a baseline single-load scenario in the subsequent analysis.

Results

The application of the two-stage algorithm to the empirical dataset yielded significant operational improvements. The algorithm evaluated a diverse pool of clients and identified an optimal consolidation variant that included the main load (Gerber) and supplementary loads (Lello, Jardin, Parmentier, Europalleten), rejecting loads that would violate physical constraints (e.g., Multiusos, which alone required **24 t** and **33 EP**). The detailed selection process is presented in table 1.

Tab. 1. Logistics parameters and optimization results for main and supplementary loads

Client	Order value (€)	Weight (t)	Volume (EP)	Selection status
Lello	1000	5.0	4	Selected (1)
Getafe	1200	8.0	18	Rejected (0)
Multiusos	2500	24.0	33	Rejected (0)
Reze	1000	15.0	15	Rejected (0)
Jardin	400	2.0	5	Selected (1)
Parmentier	650	1.0	10	Selected (1)
Europalleten	300	1.5	5	Selected (1)
Aegi	500	9.0	9	Rejected (0)
Nasser	750	12.0	13	Rejected (0)
Posnania	200	8.0	10	Rejected (0)

Client	Order value (€)	Weight (t)	Volume (EP)	Selection status
Aurora	400	4.0	7	Rejected (0)
ABC	400	13.0	15	Rejected (0)
Gerber (Main)	2875	6.0	8	Selected (1)
TOTAL / LIMIT	5225	15.5 / 24.0 t	32 / 33 EP	Constraints met

Source: own elaboration.

The consolidation process resulted in the following utilization metrics:

- **Weight Utilization:** The total loaded mass reached **15.5 t** out of the maximum **24 t** (64.5% utilization).
- **Volume Utilization:** The total cargo space occupied reached **32 EP** out of the maximum **33 EP** (97.0% utilization).

This indicates that in this specific transport scenario, the volumetric capacity (EP) acted as the critical bottleneck, rather than the physical weight.

Subsequently, the nearest neighbour algorithm was applied to determine the shortest feasible route connecting all selected nodes. The progression of the route optimization is detailed in table 2, while the final operational synthesis is presented in table 3.

Tab. 2. Iteration matrix of the nearest neighbour routing algorithm

Parameter / Iteration	I	II	III	IV	V	VI
Base node (i)	S	1	5	6	O	7
Node S	x	x	x	x	x	x
Node 1	566	x	x	x	x	x
Node 5	799	1105	x	x	x	x
Node 6	1271	1577	680	x	x	x
Node 7	1771	2077	1163	623	256	x
Node F	2875	3182	2267	1607	1360	1139
Node O	1517	1823	908	527	x	x
Current route (T)	[S, 1]	[S, 1, 5]	[S, 1, 5, 6]	[S, 1, 5, 6, O]	[S, 1, 5, 6, O, 7]	[S, 1, 5, 6, O, 7, F]
Accumulated dist.	566	1671	2351	2878	3134	4273

Source: own elaboration.

As demonstrated in table 2, the nearest neighbour algorithm sequentially builds the optimal route by systematically selecting the unvisited node with the minimum distance from the current location. Starting from Madrid (S), the algorithm successfully plotted a logical geographical progression across the Iberian Peninsula and France, incorporating the mandatory customs clearance in Mulhouse (O), before heading through Germany to the final destination in Warsaw (F).

It is crucial to emphasize that this specific sequence strictly adheres to the LIFO principle, which is a fundamental non time-dependent constraint in cargo handling. Because the selected vehicle is a standard semi-trailer accessible only from the rear doors, the loads collected last (e.g., in Stuttgart) are naturally positioned nearest to the doors, making them ready for the initial unloading phases at the destination hub. This sequencing eliminates the highly inefficient practice of unloading and reloading cargo mid-transit just to access deeper pallets. To synthesize these geographical, logistical, and operational parameters into a coherent overview, a comprehensive route roadmap has been developed and is presented in table 3.

Tab. 3. Route roadmap: Synthesis of operational, logistical, and geographical parameters

Parameter / Stage	**Stop 1 (S)**	**Stop 2 (1)**	**Stop 3 (5)**	**Stop 4 (6)**	**Stop 5 (O)**	**Stop 6 (7)**	**Stop 7 (F)**
1. Client/ Point	Gerber	Lello	Jardin	Parmentier	Gebruder	Europalleten	ALLEGRO
2. Role in system	Start/ Load	Load	Load	Load	Customs	Load	Finish/ Unload
3. City	Madrid	Porto	Toulouse	Paris	Mulhouse	Stuttgart	Warsaw
4. Country	Spain	Portugal	France	France	France	Germany	Poland
5. Coordinates	40.42, -3.71	41.15, -8.61	43.57, 1.45	48.81, 2.37	47.75, 7.31	48.78, 9.20	52.20, 21.16
6. Cargo value (€)	2875	1000	400	650	0	300	0
7. Weight (t)	6.0	5.0	2.0	1.0	0.0	1.5	15.5 (Total)
8. Volume (EP)	8	4	5	10	0	5	32 (Total)
9. Segment dist.	0	566	1105	680	527	256	1139
10. Total dist.	0	566	1671	2351	2878	3134	4273

Source: own elaboration.

The financial and operational impacts of the algorithmic consolidation are summarized by comparing the baseline scenario (main load only) with the optimized scenario (tab. 4).

- **Baseline Scenario:** Transporting only the main load generated a revenue of **2875 EUR** over a direct distance of **2875 km**, resulting in a baseline profitability indicator of **1.00 EUR/km**.
- **Optimized Scenario:** The strategic addition of partial loads increased the total freight value to **5225 EUR**. While the inclusion of additional loading points

extended the total route distance to **4273 km**, the final profitability indicator improved significantly to **1.22 EUR/km**.

Tab. 4. Comparison of economic efficiency indicators before and after optimization

Scenario	Total revenue (€)	Total distance (km)	Profitability indicator (€/km)
Baseline (main load only)	2875	2875	1.00
Optimized (with additional loads)	5225	4273	1.22

Source: own elaboration.

This **22% increase in revenue per kilometre** clearly demonstrates that the marginal cost of extending the route (additional distance) is vastly outweighed by the marginal revenue generated by filling the previously empty cargo space. Specifically, an analysis of the marginal values reveals that the additional 1398 kilometres driven to collect the supplementary loads generated an extra 2350 EUR. This translates to an impressive marginal profitability of 1.68 EUR/km for the diverted segments alone, which strongly pulls up the average profitability of the entire route.

Furthermore, this consolidation strategy significantly improves the absorption of fixed transport costs, such as driver wages, vehicle depreciation, and insurance, distributing them over a substantially larger revenue pool. Beyond the direct financial gains, maximizing the volumetric and weight fill rates directly reduces the carbon footprint per ton-kilometre. By preventing the dispatch of additional, partially empty vehicles to collect these supplementary loads, the optimized scenario strongly aligns with the principles of sustainable logistics and European environmental directives.

Conclusion

The findings of this study confirm that optimizing cargo space utilization through the rigorous application of non time-dependent constraints generates substantial economic benefits. By focusing on the structural limits of the vehicle (weight and volume) rather than delivery schedules, transport companies can significantly increase their revenue per kilometre without expanding their fleets. Specifically, the empirical case study demonstrated a 22% improvement in the core profitability indicator, elevating the average revenue from the baseline 1.00 EUR/km to 1.22 EUR/km, while successfully maximizing the volumetric fill rate to 97%.

The algorithmic approach successfully prevents operational errors, such as exceeding the legal Gross Vehicle Weight (GVW) or miscalculating pallet space, which are common in manual dispatching. Furthermore, the analysis highlights that in typical consumer goods transport, volume (cube) is exhausted much faster than weight, emphasizing the need for tools that evaluate both parameters simultaneously. Additionally, by explicitly incorporating physical cargo handling principles – such as the LIFO rule – during the routing

phase, the model eliminates inefficient mid-transit reloading, thereby reducing labor costs, loading dock times, and the risk of cargo damage.

Ultimately, integrating Knapsack and TSP algorithms into Transportation Management Systems (TMS) allows logistics operators to transition from intuition-based planning to data-driven profitability, directly supporting both enterprise margins and the broader goals of resource efficiency and sustainable transport (Ivanov, Dolgui, Sokolov, 2019; Tokarski, Bielecki, 2024). This digital transition is fully aligned with the evolving logistics paradigms of industrial revolutions, where e-logistics tools become mandatory for operational survival (Bielecki, Galińska, Tokarski, 2024). From a managerial perspective, automating these complex, multidimensional calculations relieve dispatchers from tedious manual tasks, empowering them to focus on higher-value activities such as strategic network planning, exception management, and proactive customer relations.

Despite the significant operational improvements demonstrated, this study acknowledges certain limitations that outline avenues for future research. The current model operates under deterministic assumptions and assumes static spatial constraints (standard Euro-pallets). Future studies should aim to integrate the non time-dependent physical constraints explored in this paper (weight, volume, LIFO) with the time-dependent variables analysed in the previous phase of this research (strict delivery windows), creating a holistic Vehicle Routing Problem with Time Windows and 3D Loading Constraints (3L-CVRPTW) (Iori, Salazar-González, Vigo, 2007; Gendreau et al., 2008). Furthermore, incorporating stochastic elements – such as real-time order variations, fluctuating traffic conditions, or non-standard cargo geometries – would further bridge the gap between theoretical operations research and the dynamic reality of modern supply chains (Ritzinger, Puchinger, Hartl, 2016).

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