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

Optymalizacja wykorzystania przestrzeni ładunkowej w transporcie drogowym przy ograniczeniach czasowych

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Abstract

This article evaluates the effectiveness of a simple optimization algorithm supporting cargo space utilization in international road transport under capacity and time-dependent constraints. The research focuses on identifying economically optimal additional loads that can be consolidated with a main shipment along a predefined route.

The study applies a theoretical–empirical approach, combining a literature review with a case study of a transport operation from Madrid (Spain) to Warsaw (Poland). The dataset includes twelve additional freight offers described by weight, volume, revenue, and deviation distance. The methodology involves transforming geographic coordinates into a Cartesian system, estimating a route trend line, defining an acceptable deviation corridor, and filtering feasible loads based on payload and capacity constraints. An economic evaluation is conducted using the freight-to-distance ratio (EUR/km).

The results show that the algorithm effectively reduces the time required for route planning and identifies economically viable solutions. The optimal scenario increased the freight-to-distance ratio to approximately 1.40 EUR/km, compared to a significantly lower value for the main load alone, while eliminating infeasible options.

The findings confirm that simple algorithm-based tools can improve transport efficiency, support decision-making, and

enhance capacity utilization without additional investments, contributing to economic performance and sustainability.

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

Streszczenie

Celem niniejszego badania jest ocena skuteczności algorytmu optymalizacyjnego wspierającego wykorzystanie przestrzeni ładunkowej w międzynarodowym transporcie drogowym przy uwzględnieniu ograniczeń ładowności oraz ograniczeń czasowych. Badanie koncentruje się na identyfikacji ekonomicznie optymalnych ładunków dodatkowych, które mogą zostać skonsolidowane z ładunkiem podstawowym na z góry określonej trasie. W pracy zastosowano podejście teoretyczno-empiryczne, łączące przegląd literatury z analizą studium przypadku operacji transportowej na trasie Madryt (Hiszpania) – Warszawa (Polska). Zbiór danych obejmuje dwanaście ofert ładunków dodatkowych opisanych za pomocą parametrów takich jak masa, objętość, przychód oraz dodatkowy dystans. Metodyka obejmuje transformację współrzędnych geograficznych do układu kartezjańskiego, estymację linii trendu trasy, wyznaczenie dopuszczalnego korytarza odchyień oraz filtrację wykonalnych ładunków na podstawie ograniczeń technicznych (ładowność i pojemność). Ocena ekonomiczna została przeprowadzona z wykorzystaniem wskaźnika frachtu do odległości (EUR/km).

Wyniki wskazują, że algorytm skutecznie ogranicza przestrzeń decyzyjną oraz identyfikuje rozwiązania ekonomicznie opłacalne. Optymalny wariant zwiększył stosunek frachtu do odległości do około 1,40 EUR/km w porównaniu do znacznie niższej wartości dla samego ładunku podstawowego, jednocześnie eliminując rozwiązania niewykonalne.

Wnioski potwierdzają, że nawet proste narzędzia oparte na algorytmach mogą znacząco poprawić efektywność transportu, wspierać procesy decyzyjne oraz zwiększać wykorzystanie zdolności przewozowych bez konieczności dodatkowych inwestycji, przyczyniając się do poprawy wyników ekonomicznych oraz zrównoważonego rozwoju.

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

Introduction

Efficient organization of freight transport is one of the fundamental determinants of competitiveness in contemporary logistics systems and supply chains. In the conditions of progressing globalization, growing fragmentation of production processes,

and increasing expectations of customers regarding delivery time and reliability, logistics efficiency becomes a strategic factor for enterprises operating in the Transport–Spedition–Logistics (TSL) sector. Road transport, despite the growing importance of intermodal and rail-based solutions, remains the dominant mode of freight carriage in Europe, particularly in Central and Eastern Europe. Its flexibility, high availability, dense infrastructure network, and relatively low entry barriers make it indispensable for both domestic distribution systems and international supply chains.

At the same time, road transport faces increasing economic and organizational pressure. Rising fuel and energy prices, chronic shortages of qualified drivers, stricter social regulations, and tightening environmental requirements imposed by the European Union significantly affect transport costs and operational planning. Enterprises are therefore forced to seek internal reserves of efficiency that do not require immediate capital-intensive investments in fleet expansion or infrastructure development.

One of the most frequently identified operational inefficiencies in road freight transport is the underutilization of cargo space and payload capacity. Vehicles often travel with partially filled loading units, particularly on long international routes, which results in higher unit transport costs, unnecessary fuel consumption, increased emissions, and intensified congestion. Numerous empirical studies indicate that improving vehicle load factors constitutes one of the most effective ways to enhance transport efficiency without additional infrastructure investments (McKinnon, 2018; Browne, Allen, Leonardi, 2019).

The relevance of cargo space optimization is strongly emphasized in European transport policy. The White Paper on Transport published by the European Commission in 2011 explicitly calls for the development of new transport patterns that enable the carriage of larger volumes of goods using more efficient transport means or their combinations, while limiting the use of individual transport to final delivery segments (*White Paper on Transport: Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*, 2011). These objectives are closely linked to the broader concept of sustainable transport, which integrates economic efficiency, environmental protection, and social responsibility. In this context, better utilization of existing transport resources is treated as a priority instrument for achieving sustainability goals.

In practical terms, decisions concerning load consolidation and route planning are still very often made manually by dispatchers and forwarders, based on professional experience, intuition, and informal heuristics rather than systematic analytical tools. While human expertise remains valuable and irreplaceable in non-standard situations, repetitive decision-making tasks are particularly prone to errors, cognitive overload, and inefficiencies, especially in environments characterized by large data volumes and time pressure. As highlighted in the literature on decision support systems, algorithm-based solutions can significantly improve decision quality, consistency, and transparency while simultaneously reducing operational costs (Power, 2002; Turban, Sharda, Delen, 2011).

Against this background, the present paper addresses the problem of optimizing cargo space utilization in road transport through the application of a simple analytical algorithm integrated with a Transportation Management System (TMS). Particular attention is paid not only to the direct economic effects of optimization, but also to its organizational implications, especially in the area of human resource management. The study additionally examines the consistency of the proposed solution with the objectives of sustainable transport policy and the broader paradigm of Industry 4.0.

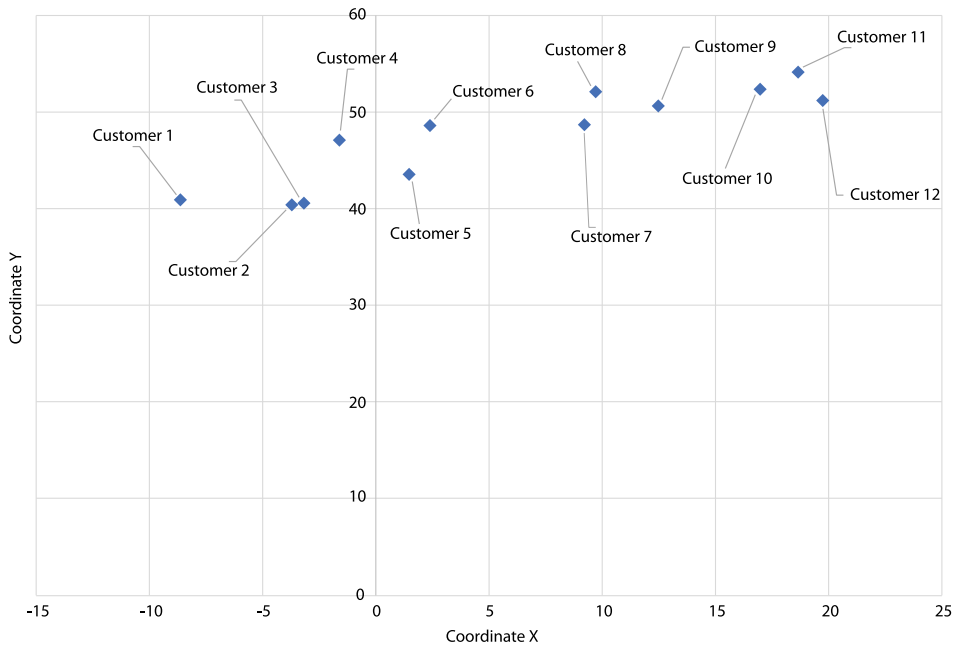


Fig. 1. Projection of geographic coordinates onto a Cartesian plane

Source: own elaboration.

Figure 1 presents the transformation of real geographic coordinates of shipment origin and destination points into a Cartesian coordinate system, enabling further spatial analysis and the identification of potential additional loads along the transport route.

Research purpose and methodology

The main purpose of this research is to evaluate the effectiveness of a simple optimization algorithm supporting the selection of additional loads in international road transport, taking into account vehicle capacity constraints, spatial conditions, and route-related requirements. The study seeks to demonstrate that even non-complex

analytical tools can generate tangible economic benefits when compared to traditional, manual planning approaches commonly used in transport enterprises.

The specific objectives of the research are fourfold. First, the study aims to identify economically attractive additional loads that can be consolidated with a main freight along a predefined international route. Second, it seeks to assess the impact of load consolidation on the freight-to-distance ratio (expressed in EUR/km), which is one of the key indicators of transport profitability. Third, the research compares algorithm-based decision-making with human labour in repetitive planning tasks, highlighting potential savings in labour costs and planning time. Finally, the study evaluates the compliance of the proposed solution with European Union transport policy and sustainable development principles.

The research adopts a theoretical–empirical approach. The theoretical framework is grounded in the literature on transport logistics, freight transport optimization, decision support systems, and sustainable transport. The empirical component takes the form of a case study, which is particularly suitable for analysing complex operational decision-making processes embedded in real organizational contexts (Yin, 2018). The case study method enables an in-depth examination of cause–effect relationships and allows theoretical concepts to be tested in practical settings.

The empirical analysis concerns a heavy goods vehicle with a maximum payload of 24 tons and a cargo capacity of 33 Euro-pallet units, performing an international transport task from Madrid (Spain) to Warsaw (Poland).

Tab. 1. Intermediate points along the transport route with the main load

Intermediate points along the route	Coordinate X	Coordinate Y
Madrid (Loading)	-3.7144070	40.4183430
San Sebastian	-1.987278	43.312824
Bordeaux	-0.574672	44.837555
Riom	3.110211	45.89043
Mulhouse (Customs)	7.337201	47.755428
Heillbron	9.217236	49.168183
Nuremberg	11.119931	49.428341
Hof	11.913693	50.330069
Dresden	13.729871	51.078457
Wroclaw	17.031262	51.156042
Lodz	19.500593	51.756958
Warsaw (Destination)	21.162941	52.195253

Source: own elaboration.

The table 1 includes intermediate points marked on the basic route of the vehicle with the main load, which constitute a reference for further determination of the trend

line and the scope of search for additional loads. An obligatory element of the route is a customs clearance stop in Mulhouse (France), which constitutes a time- and space-dependent constraint affecting route planning. The main load occupies approximately 25% of the vehicle's payload and cargo space, which creates substantial potential for consolidation with additional loads without exceeding technical limits.

The dataset used in the study comprises twelve additional freight offers submitted by shippers located along or near the base route.

Tab. 2. Freight offers submitted by shippers together with their parameters

No. customer	Geographic coordinates	(wi) [t]	(qi) [EP – 120x80]	(si) [EUR]	(ri) [km]	(pi) [EUR/km]
1	X = 41.146903 Y = -8.614774	5	4	1000	961	1.010
2	X = 40.454438 Y = -3.676484	8	18	1200	10	1.403
3	X = 40.638654 Y = -3.165641	24	33	2500	28	1.831
4	X = 47.195542 Y = -1.566590	15	15	1000	355	1.195
5	X = 43.567935 Y = 1.451603	2	5	400	119	1.092
6	X = 48.814601 Y = 2.370061	1	10	650	295	1.110
7	X = 48.781314 Y = 9.200768	1.5	5	300	35	1.089
8	X = 52.366924 Y = 9.737542	9	9	500	143	1.116
9	X = 50.704912 Y = 12.481193	12	13	750	12	1.249
10	X = 52.396675 Y = 16.954017	8	10	200	66	1.044
11	X = 54.338138 Y = 18.607002	4	7	400	394	1.002
12	X = 51.405955 Y = 19.739797	13	15	400	8	1.133

Source: own elaboration.

The table 2 presents a summary of additional loads reported by suppliers, including their weight, volume, economic value, and geographic location. This data constitutes the basic input data for the additional load selection algorithm. For each offer, data are available on cargo weight, pallet space requirements, freight value, additional distance, and the resulting EUR/km ratio. Such datasets are characteristic of Transportation Management Systems used in the TSL sector and reflect real decision-making conditions faced by dispatchers and forwarders.

The methodological procedure consists of several stages. First, the base route is spatially mapped using geographic coordinates of key points, including the origin, destination, and mandatory intermediate stop. Second, a linear trend line representing the main transport corridor is estimated. Third, an acceptable deviation corridor is defined to identify potential additional loads that do not cause excessive detours. Fourth, additional loads located within this corridor are verified with respect to payload and cargo space constraints. Finally, feasible solutions are evaluated using economic criteria, primarily the freight-to-distance ratio. Two optimization variants are considered: Variant I, involving a single additional load, and Variant II, involving the combination of multiple additional loads. Due to space limitations, the present paper focuses on Variant I, which already provides robust and illustrative insights.

Results

The empirical results clearly demonstrate that the proposed algorithmic approach effectively supports the identification of economically advantageous additional loads in international road transport.

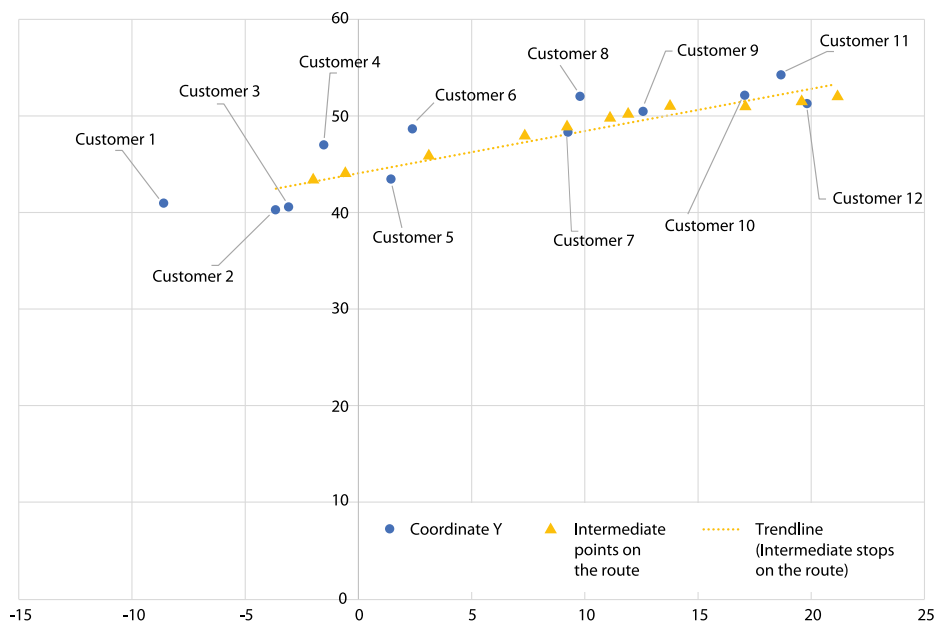


Fig. 2. Projection of geographic coordinates onto a Cartesian plane with the marked search area for additional loads – Step 2

Source: own elaboration.

The figure 2 presents the trend line determined on the basis of the main route’s intermediate points and the preliminary search corridor for additional loads, enabling

the elimination of offers that generate excessive deviations from the base route. The spatial analysis significantly reduced the initial set of freight offers, confirming the usefulness of simple spatial filtering techniques in supporting decision-makers.

Subsequent verification against payload and cargo space constraints further reduced the number of feasible options, eliminating solutions that would exceed the vehicle's technical limits. This step is of critical importance, as neglecting physical constraints is one of the most common sources of infeasible or costly decisions in manual planning processes (Crainic, Laporte, 1997). The algorithm ensures that only technically feasible solutions are considered at later stages of economic evaluation.

Within Variant I, the most advantageous solution involved the consolidation of the main freight with an additional load originating from Getafe (Spain).

Tab. 3. Y-values of points located on the trend line corresponding to real geographic points

Coordinate \hat{y}
42.6402049
43.3840794
43.9924888
45.5795679
47.4001325
48.2098635
49.0293543
49.3712276
50.1534554
51.5753645
52.6389054
53.3548787

Source: own elaboration.

Tab. 4. Y-coordinates of the line defining the upper search boundary

Coordinate y^{+d}
44.7831397
45.5270141
46.1354235
47.7225026
49.5430672
50.3527983
51.1722890

Coordinate y^{+d}
51.5141623
52.2963902
53.7182993
54.7818402
55.4978134

Source: own elaboration.

Tab. 5. Y-coordinates of the line defining the lower search boundary

Coordinate y^{-d}
40.4972701
41.2411446
41.8495540
43.4366331
45.2571977
46.0669288
46.8864195
47.2282928
48.0105207
49.4324298
50.4959706
51.2119439

Source: own elaboration.

Table 3 contains the y-coordinate values determined on the trend line that correspond to actual geographic locations. This data is necessary for defining acceptable deviation limits in the subsequent stage of the algorithm.

Table 4 presents the limit values defining the upper range of permissible deviations from the trend line.

Table 5 includes similar limit values for the lower range of cargo searches.

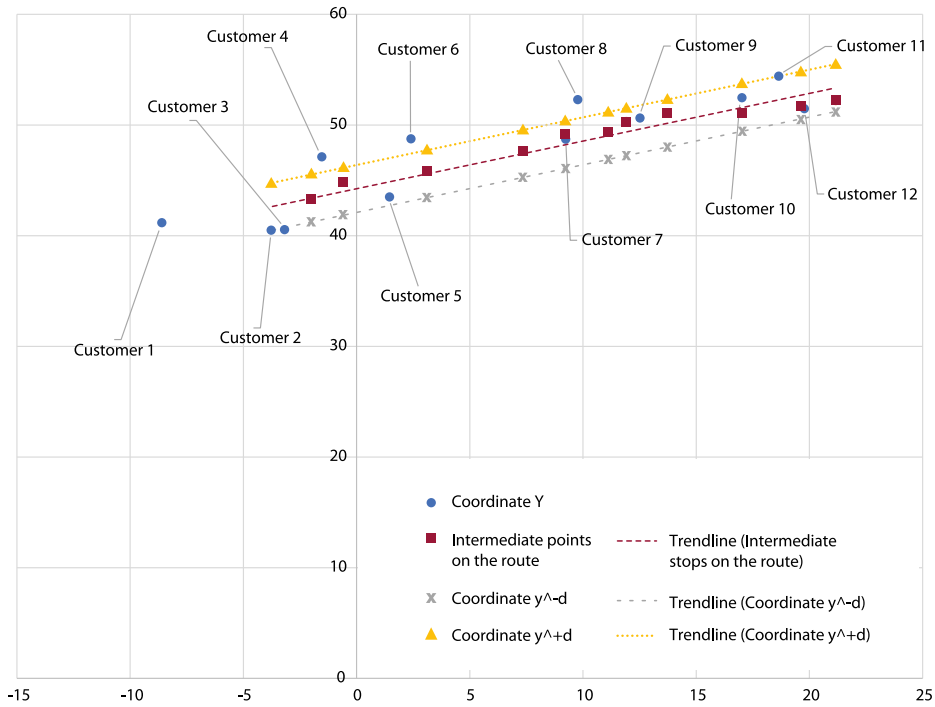


Fig. 3. Projection of geographic coordinates onto a Cartesian plane with the marked search area for additional loads – Step 3

Source: own elaboration.

Figure 3 illustrates the final stage of spatial filtering of additional load offers after applying the upper and lower boundary lines.

Tab. 6. Comparison of the characteristics of consolidated additional transports and the main transport

No. customer	(wi) [t]	(qi) [EP]	(si) [EUR]	(r) [km]	(p) [EUR/km]	(wi+ws)	(qi+qs)
2	8	18	1200	10	1.403	14	26
3	24	33	2500	28	1.831	30	41
5	2	5	400	119	1.092	8	13
7	1.5	5	300	35	1.089	7.5	13
9	12	13	750	12	1.249	18	21
10	8	10	200	66	1.044	14	18
11	4	7	400	394	1.002	10	15
12	13	15	400	3948	1.133	19	23

Source: own elaboration.

Table 6 summarizes the key parameters of the main transport and selected additional loads, confirming the economic and organizational justification of the solution used. This combination increased the freight-to-distance ratio to approximately 1.40 EUR/km, compared to the significantly lower value obtained for the main load transported alone. The improvement illustrates how even a single well-selected additional load can substantially enhance transport profitability over long international routes, particularly when the base load does not fully utilize vehicle capacity.

Beyond direct economic gains, higher cargo space utilization leads to improved resource efficiency. Increased load factors reduce unit transport costs, fuel consumption per ton-kilometre, and greenhouse gas emissions, thereby contributing to environmental objectives emphasized in sustainable transport policy (McKinnon et al., 2015). From a system-level perspective, improved utilization of existing vehicle capacity may also contribute to reduced traffic volumes and congestion.

The results also highlight important organizational and managerial implications. The analysed decision problem represents a repetitive and time-consuming task typically performed by dispatchers and forwarders on a daily basis. The findings indicate that algorithm-based planning can deliver outcomes that are at least comparable, and often superior, to manual planning, while requiring significantly less time and lower labor costs. This observation is consistent with broader research on digitalization and Industry 4.0, which emphasizes productivity gains through the automation of routine analytical and decision-making processes (Ivanov, Dolgui, Sokolov, 2019).

Conclusion

The study confirms that optimizing cargo space utilization in road transport through data-driven, algorithmic methods yields measurable economic, operational, and environmental benefits. The proposed approach enables transport enterprises to improve profitability without additional fleet investments, relying instead on more efficient use of existing technical and organizational resources.

From a practical standpoint, integrating simple optimization algorithms with Transportation Management Systems enhances decision quality, reduces planning time, and limits the risk of suboptimal or infeasible choices. Importantly, the study demonstrates that advanced benefits can be achieved with relatively simple analytical tools, which lowers implementation barriers for small and medium-sized transport companies that often lack access to sophisticated optimization software.

From a managerial and human resource perspective, the results support the strategic substitution of repetitive planning tasks with algorithmic solutions. Such substitution allows employees to focus on higher-value activities, including negotiation, customer relations, and strategic coordination. This approach is consistent with continuous improvement concepts, including Kaizen, and contributes to improved job satisfaction by reducing the burden of routine tasks.

Finally, the proposed solution aligns closely with the objectives of European transport policy, sustainable development, and the broader framework of Industry 4.0. By improving resource efficiency and reducing environmental externalities, cargo space optimization contributes to long-term competitiveness and sustainability of the road transport sector. Future research should extend the model to incorporate explicit time-dependent constraints, real-time traffic data, and stochastic demand, as well as validate the approach through longitudinal implementation studies in transport enterprises.

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