Enhancing Freight Transport Efficiency in Germany Through Multimodal Route Optimization

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Abstract. Freight transport is a major contributor to Europe's greenhouse gas emissions, a trend expected to intensify with rising delivery demands. Multimodal transport has gained attention to reduce emissions as electrification of road freight transport is progressing slowly. However, identifying such multimodal routes remains a challenge for companies aiming to adapt their logistics operations. This paper presents a graph-based route optimization tool for such multimodal routes based on road and rail data from OpenStreetMap. Intermodal stations are modeled as connection nodes between the two networks, and edge weights are defined according to multiple evaluation criteria. Four optimization objectives are investigated: distance, time, cost, and emission. Dijkstra's algorithm is applied to compute optimal routes for each objective across the multimodal graph. Results show that the tool can provide feasible multimodal routes within practical execution times of around 40 s for a network covering all of Germany. Cost-based optimization tends to favor road transport due to comparatively low pricing, whereas emissions-based optimization consistently yields rail solutions. The study demonstrates the potential of combining open data with graph algorithms to support sustainable logistics planning and provides a foundation for further extensions to larger-scale and cross-border freight networks.

Keywords: Multimodal transport · Graph-based route optimization · Sustainability

1 Introduction

The European Union's freight transport activity has significantly grown over the past decades, reaching 3,471 billion tonne-kilometers in 2022 [13]. This growth

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tendency is expected to continue in the following years since freight transport is expected to grow by 29.6% in volume compared to the 2015 scenario [13]. The urgency to find feasible solutions for decarbonization is clear, since the transport sector in the EU accounted for 29% of total greenhouse gas (GHG) emissions in 2022 [40], with freight transport being responsible for 30% of the sector's CO_2 emissions [11]. This is due to the dominant use of road freight for land transport that relies on fossil fuels. According to Eurostat, domestic road freight transport in the EU in 2022 accounted for 77.8% of total domestic freight traffic through the region [14]. While innovative sustainable concepts such as electric, autonomous deliveries exist for last mile logistics [21,24], the electrification of long haul heavy-duty vehicles is advancing slowly, with electric trucks accounting for only 2.2% of sales in Europe in 2024 [18], despite ongoing efforts through various electrification strategies [16,22,26,41,42].

Another way of reducing GHG emissions is through multimodal transport, particularly by increasing the share of goods transported by rail, as transporting goods by truck emits on average five times more CO_2 per tonne-kilometer than by train [12]. However, shifting freight from road to rail is not always straightforward, as it requires careful consideration of infrastructure availability, logistics constraints, and overall efficiency [25,37]. Given this context, it becomes essential to determine the most effective multimodal transport routes. Not only should the most cost-effective and time-efficient options be identified, but also the routes that minimize environmental impact.

In this work, we propose a graph-based route optimization algorithm considering different criteria, i.e., distance, time, cost, and emission, with the full implementation publicly available in our GitHub repository [23]. We create a multimodal network and identify transfer points based on the open data framework OpenStreetMap, and suggest weight factors for each criterion. Dijkstra's algorithm is subsequently applied to the weighted graphs to find the optimal route subject to the respective criterion. The rest of the paper is structured as follows. In Sect. 2, we review relevant literature on route optimization. The proposed algorithm is detailed in Sect. 3. The results are presented in Sect. 4 and the paper is concluded in Sect. 5.

2 Literature Review on Route Optimization Models

The optimization of freight transport routes has become a topic of growing interest, both in research and in the logistics industry. In recent years, research has expanded to multimodal transport, aiming to find the optimal way of moving goods using different transportation modes. Previous research on routing optimization in logistics has largely focused on reducing cost and travel time. Kaewfak et al. [20] developed a multi-objective model based on Zero-One Goal Programming to reduce transport cost and transport time, also taking into account seven risk factors that could affect the transportation route. Bhattacharya et al. [1] aimed to minimize the total supply chain costs and transportation times of freight transport in India, taking road traffic congestion as the main criterion for deciding whether to use a multimodal route or not. Pedersen [36] proposed a different approach, considering a time-based network where arcs between nodes represent feasible time slots during which a train can travel between points. The objective function of this mixed integer mathematical programming model is also the minimization of fixed costs such as railway construction costs and variable costs such as transportation costs, as well as the expenses related to transportation time. The DiSTILL map [8] offers multimodal routing that integrates train and truck transportation and provides detailed information on distance, time, cost, and emissions. However, it generates routes only based on the shortest distance criterion, and mode changes must be specified manually by the user.

A number of studies have examined the multimodal routing problem from an environmental perspective. Wang et al. [44] included CO_2 emission costs as one of the elements in the objective function of a fuzzy mixed integer linear programming model aimed at minimizing overall costs. This was applied to improve freight transport routes in Vietnam while also addressing other logistics aspects such as node capacity, detours, and vehicle utilization. Chen et al. [4] tackled the problem of choosing optimal multimodal routes for cargo with different value and time sensitivities. They proposed a model that minimizes the combined cost of carbon emissions and delivery time, adapting transport mode choices based on cargo attributes. A sensitivity analysis is included to assess how policy changes affect route decisions.

Despite the fact that the reviewed studies take into account multimodal transport and emissions reduction, most of them are built for very specific cases or under fixed assumptions such as limited numbers of transfer points and coarse network nodes on city level. This makes it difficult to apply their results to other scenarios or to use them as general tools for routing. There is still a need for a routing model that can offer optimal routes based on different user-defined preferences. A model like this should be able to adapt to different inputs, and provide routing that evaluates cost, time, and environmental impact according to the user's needs. This would make it easier to apply optimization models to real-life transport decisions in a more flexible and useful way.

3 Methodology

3.1 Multimodal Network Generation from OpenStreetMap Data

The German railway network spans 38,691 km and is one of the densest in Europe with approximately 109.5 m of railway line per km^2 [14]. Germany's road network is similarly extensive, comprising about 50,956 km of federal trunk roads (Bundesfernstraßen) [2]. In order to determine the optimal route for freight transport, it is important to have an accurate representation of these networks as well as the transfer points. In this work, the network data and transfer points are retrieved from OpenStreetMap (OSM) [29] using the Overpass API [35].

OSM Road Network. OSM has a tagging system that helps identify the features of its elements. In the road network, the main key used to designate

Table 1. Main OSM road types for the German network [31].

Value	Description
motorway	Federal motorway (Autobahn). Dual carriageway with separated directions, with usually two or more lanes per direction and an emergency lane.
trunk	Major road similar to a motorway ("gelbe Autobahnen").
primary	Federal highway (Bundesstraße). Designates main national roads connecting major cities, and also serves interregional traffic.
secondary	State or well-developed district road (Landesstraße/Staatsstraße/Kreisstraße). Connects smaller cities or towns and serves regional traffic.

roads is *highway*. The most relevant road categories for freight transport are *motorway*, *trunk*, *primary*, and *secondary* shown in Table 1. Some road elements are tagged as connecting roads using values such as *motorway_ link*, *trunk_ link*, or *primary_ link*. These links must be included since they designate connections between different types of roads, and without them the network would be incomplete and the road types disconnected.

OSM Rail Network. To obtain the data related to the railway infrastructure in Germany, the same procedure as for the road network is pursued. The *railway=rail* tag is used to designate rail infrastructure. It is assumed that the entire rail infrastructure is available for freight transport in the absence of more specific information.

Connection Edges. The most important edges in a multimodal network are where the mode of transport can be changed, i.e., intermodal terminals. Not all intermodal terminals are tagged consistently in OSM, and there are several tags that can be used to refer to different kinds of rail stations. Therefore, we use a set of tags, shown in Table 2, that can be used to look for nodes or areas that represent such types of facilities, which we refer to as points of interest (POIs). The wide scope of tags is a deliberate choice to not miss any potential transfer points and provide a flexible network for the simulation. For real use cases, the search should be much more refined and a database should be created for actual intermodal terminals such as in [39].

The search outputs 4909 elements which are further filtered. All POIs labeled *abandoned* or *disused* are dismissed, and only the points labeled *no* for *public_ station* are treated as intermodal terminals, as *public_ station* explicitly designates stations used for public transport. 4254 of the potential locations are

Table 2. OSM tags used to identify POIs.

Tag (key=value)	Number of points	Description
railway=station	151	Designates a facility where trains load and unload passengers or goods [33].
railway=yard	400	Series of rail tracks used for sorting or storing railway wagons and locomotives [34].
railway=container_terminal	53	Terminal for freight transportation [32].
building=station	51	Building constructed to be a train station, for passengers or goods [30].
Total number of POIs	655	

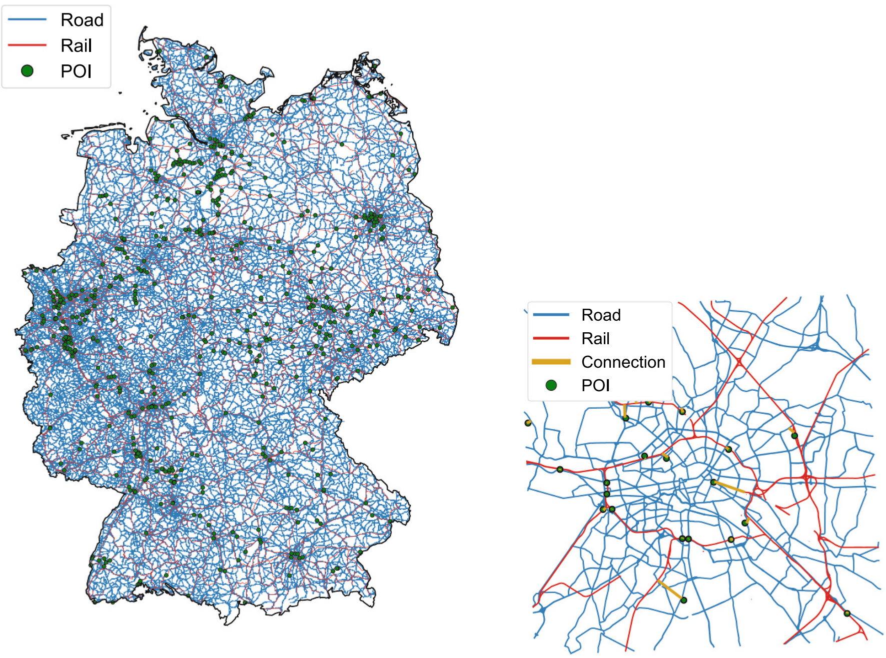
discarded, leaving a total of 655 POIs. Table 2 displays the distribution of the final POIs based on their tag.

The final POIs are used to create the connection edges by searching for the nearest node in both the road and rail networks to each POI. If the distance to the nearest road node is less than 15 km, and less than 3 km to the nearest rail node, the POI is considered suitable for the network, and a connection edge is established between the nearest road and rail nodes. Not all POIs have nearby nodes in the road and rail network that satisfy these conditions so that the number of connection edges is lower than the number of POIs.

Assembling the Final Multimodal Network. Once the road and rail networks are retrieved and the connection edges are determined, both networks are merged into a multimodal network connected through the connection edges. The full multimodal network is shown in Fig. 1 and its properties in Table 3.

Table 3. Multimodal network properties.

Network element	Road edges	Rail edges	Connection edges
Count	929,050	103,848	597



(a) Multimodal network in Germany. (b) Close up view of Berlin.

Fig. 1. Final multimodal network of Germany with POI, and road, rail, and connection edges.

3.2 Criteria Definition and Graph Construction

The graph obtained from OSM serves as the foundation for building a weighted graph to be used with Dijkstra's algorithm. Since this mathematical method will be applied to optimize different criteria, a set of graphs will be constructed to represent the characteristics of each node and edge in terms of cost, time, and environmental impact. The main aspect to address is how to determine the weight of each edge, considering that the algorithm will search for the path with the lowest total weight.

In order to generate these graphs, certain assumptions will be made to make the problem more feasible and realistic. These statements are the following:

1. The algorithm is designed to optimize costs, emissions, or times strictly related to the transport route itself. External costs or emissions not directly caused by the route will not be considered.
2. To simplify and standardize the calculations, the amount of goods will be expressed in number of twenty-foot equivalent units (TEUs).
3. The multimodal transport will be carried out in swap bodies, a transport container that can be easily attached to a truck and also to a railway platform. The considered swap bodies are 40 ft long equivalent to two TEUs.

4. The heavy goods vehicles for the road transport carry one swap body (2 TEUs) and the freight trains carry forty swap bodies (80 TEUs).
5. According to German road legislation, a truck may not exceed a total weight of 40 t [15]. Considering the weight of the heavy goods vehicle itself, the maximum payload that the swap bodies can transport is 23 t. Since one swap body is equivalent to two TEUs, the weight of one TEU is considered to be half of the total weight: 11.5 t. Cost factors depend on the weight of the cargo.

The length of each road and rail edge in the graph is given by the OSM data. Each criterion will be defined based on the edge length. On the other hand, the weights of the connection edges, which represent the transfer operations between road and rail, will not be defined based on the edge length, but according to the actual characteristics and implications of the transfer process. It is crucial to properly define the weights of the connection edges to ensure that realistic multimodal routes are generated while avoiding an excessive number of transfer operations.

Distance. For the distance graph, the weight of the edges is defined as the distance in meters between the two nodes they connect. This attribute is taken directly from the length provided by OSM for both the road and rail network edges as well as the connection edges.

Time. For road and rail edges, the required time to travel the edge's distance is calculated considering the average speed of trucks or trains on the routes. The speed limit on German roads varies depending on the type of road. Since the graph network is composed of roads with different characteristics, a distinction is made in terms of speed. According to [7], trucks are allowed to drive at a maximum speed of 80 km/h on main roads and highways, while on secondary or rural roads, the limit decreases to 60 km/h for vehicles over 7.5 t. According to [17], the average train speed for freight transport is 55 km/h.

Burdzik et al. [3] analyze the usual steps involved in loading or unloading goods on a multimodal transport route. The most relevant activities in the process (excluding container loading or unloading) have been selected, and their duration in minutes is used as a reference to estimate the time needed for the transfer operation. The values are shown in Table 4.

Table 4. Estimated times for loading and unloading transfer operations [3].

Task	Description	Time (min)
Arrival	Arrival of the trucks to the terminal, includes documentation management	31
Waiting time	Average waiting time to load or unload the trucks	60
Departure	Includes securing cargo and leaving the terminal	20

For the loading and unloading of the swap bodies, it is assumed that the cargo is moved directly from the truck to the train platform or vice versa, so no intermediate storage times are considered. An average of 100 s is assumed for the loading or unloading of one TEU [28]. Once this criterion is defined, the expression for the operation time in hours during the mode change at an intermodal station is given as follows.

$$t = 1.85 + 0.028 * q \tag{1}$$

where t is time in hours and q is the number of TEUs to be transferred. This expression is used for the connection edges. Table 5 summarizes all expressions for the time-weighted edges.

Table 5. Time weight expressions for each edge type in the network.

Edge type	Time weight expression (h)
Road (motorway/trunk/primary)	$l/80$
Road (secondary)	$l/60$
Rail	$l/55$
Connection	$1.85 + 0.028 \cdot q$

Cost. *Rail Transport.* According to [27], DB InfraGO released a report in 2023 stating that the price for transporting goods by rail in Germany would increase 16% during 2024, reaching the value of 3.73 €/km. This price, together with the assumption that one train carries 80 TEUs, the final price for train transportation for a TEU unit is 0.05 €/TEU·km. This value takes into account all the expenses generated in the transport through the railway system for one TEU.

Road Transport. The road transport cost takes into account two main elements. The first considers the average price per km offered by transportation companies. The second is a toll applied to every truck that travels on German roads. This charge is based on factors such as vehicle weight and emissions. To determine the average price per km in road transport, data offered by Della, a road transportation company, have been analyzed. The company displays the price for their most recent orders on routes within Europe, giving an overview of the origins and destinations, the transport volume, and the average price per km. This data was checked on the 13^{th} of August 2025, and is displayed in Table 6 for transport distances between 300 km and 800 km, considering the size of Germany. The average price per km is determined by calculating the mean of the routes in Table 6, which yields an average transport cost of 1.99 €/km.

The road toll depends on the type and weight of the vehicle. For this study, Euro 6 trucks are selected, which are the most common tractor-trailers [38]. Assuming a payload of 23 t per truck and based on the data presented in [43], the toll to be considered is 0.30 €/km. The final price per km for road transportation is then 2.29 €/km·truck or 1.145 €/km·TEU.

Table 6. Della's freight transport routes between 300 km and 800 km and rates from 13.08 [5].

Route	Distance	Load	Rate	Price per km
Włocławek—L'viv	697 km	22 t	1100.00 EUR	1.58 EUR/km
Warsaw—L'viv	399 km	22 t	1200.00 EUR	3.01 EUR/km
Lublin—Ternopil	346 km	22.5 t	700.00 EUR	2.02 EUR/km
Shostka—Chisinau	769 km	20 t	1200.00 EUR	1.56 EUR/km
Brześć Kujawski—L'viv	703 km	20 t, 86 m^3	1250.00 EUR	1.78 EUR/km

Connection Edges. Hintjens et al. [17] compare prices for various activities in logistics operations from a case study. The study gives an average cost of 50 €/TEU for container transfers, which will be taken as the cost of the connection edges. Table 7 displays the cost parameters for each edge type based on the number of transported TEUs q and edge length l.

Table 7. Cost expression for each edge type in the network.

Edge type	Factor	Expression (€)
Rail	0.05 €/km·TEU	$0.05 \cdot q \cdot l$
Road	1.145 €/km·TEU	$1.145 \cdot q \cdot l$
Connection	50 €/TEU	$50 \cdot q$

Emissions. The emissions generated by road transport are determined using a factor that estimates the average grams of CO_2 per tonne·km transported. A preliminary estimate of the CO_2 emission performance of new heavy goods vehicles in Europe registered during a specific period in 2019 is given in [10]. The real performance of different types of freight vehicles is analyzed using VECTO (Vehicle Energy Consumption Calculation Tool). Because we assume that trucks will be transporting 40 ft swap bodies, the subgroup that best fits our problem is the 9-LH vehicles that are long-haul vehicles with 4×2 tractor configurations. The average CO_2 emission is given as 64.7 g/t·km for a payload of 13.4 t. The values provided are only for the transport of a single TEU, and considering that the trucks in this specific problem will be transporting two TEUs, the final value is doubled to remain consistent. The resulting factor for road edges is 129.4 g/t·km. Regarding the emissions from rail transport, an article released by [9] states that an average freight train emits 24 g CO_2/t·km transported, which is adopted for this study.

For the connection edges, the emissions are produced by reach stackers during the loading and unloading of the swap bodies. Assuming a reach stacker model SMV 4123 CC5 from the Konecranes company, which consumes about

16 l Diesel/h, and a transfer time of 100 s per TEU, a transfer produces 2.36 g CO_2 per TEU. This can be neglected, as one truck with a payload of 23.5 t would produce 2978.5 g CO_2 per km. Table 8 presents the final expressions used to calculate emissions for each edge in the emissions graph.

Table 8. CO_2 emissions expressions for each edge type in the network.

Edge type	Factor	Expression (g CO_2)
Rail	129.5 g CO_2/tkm	$129.5 \cdot q \cdot w \cdot l$
Road	24 g CO_2/tkm	$24 \cdot q \cdot w \cdot l$
Connection	0	0

3.3 Dijkstra's Algorithm for Multimodal Transport Routes

One of the most used algorithms in route finding is Dijkstra's algorithm, which is used to find the shortest path between two points in a weighted graph. As described in [19], given a graph with a set of nodes connected by edges that have been assigned a weight, the algorithm begins an iterative process to determine the shortest path according to these weights, from an origin point A to a destination point B. This methodology ensures that the final path is the shortest route from A to B, since in every iteration each node's distance is updated to the shortest length known at that stage.

What was originally defined as length can be generalized to weights, allowing the algorithm to be applied to other domains, such as cost or time optimization. For this purpose, multidigraphs based on the geographic network retrieved from OSM are generated with weights calculated from the factors presented in Sect. 3.2 and the number of TEUs q that are considered. After the origin and destination points are designated, Dijkstra's algorithm is applied to find the shortest, and thus, optimal route for the specific case and criterion.

4 Algorithm Validation and Performance Analysis

In this section, the performance of Dijkstra's algorithm in a multimodal network is analyzed. First, a validation of its right processing of data will be conducted. After that, the behavior of the algorithm according to different criteria will be examined. These analyses have been conducted considering different locations around Germany. Most of these locations have been selected because of the type of industry around that area (Munich) or because of its other logistics facilities (Hamburg because of its port), since this implies a higher flow of goods in the city, and therefore it makes it more interesting to see how the algorithm creates routes from these logistically relevant hubs. To designate each of these locations, a single point has been selected.

4.1 Algorithm Validation

The distance graph has been used to validate that the algorithm finds the shortest route between the origin and destination point. Table 9 displays the description of the validation tests, as well as their final route length (both by road or rail). On average, Dijkstra's algorithm needs 40.55 s to find the optimal path in the provided network.

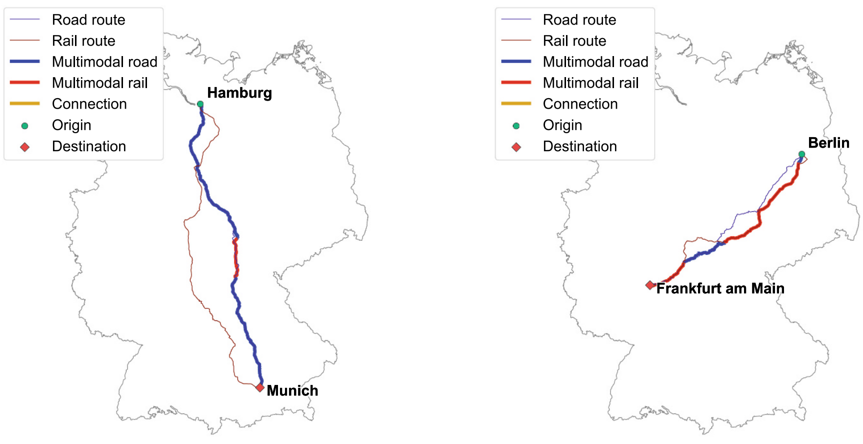
Table 9. Summary of validation routes.

Origin	Destination	Transport mode	Total route length (km)	Road route (km)	Rail route (km)
Hamburg	Munich	Multimodal[1]	718.97	628.27	90.6
		Only road	729.96	729.96	0
		Only rail	804.42	0	804.42
Berlin	Frankfurt am Main	Multimodal[2]	512.09	149.01	361.53
		Only road	517.86	517.86	0
		Only rail	546.37	0	546.37

[1] Connection length of 0.10 km,
[2] connection length of 1.56 km.

Two scenarios - from Hamburg to Munich and from Berlin to Frankfurt am Main - are analyzed and the routes are shown in Fig. 2. The multimodal route is always the shortest with more road segments for the route from Hamburg to Munich, and with more rail segments for the route from Berlin to Frankfurt am Main. In both cases, the route taking only the rail is the longest. As can be seen in Fig. 2, in both multimodal routes large parts of the route overlap with those of the road only or rail only routes. For the scenario from Hamburg to Munich, the multimodal route is almost identical to the road route with a section in the middle being shifted to rail, which overall reduces the total route length by 11 km. The total multimodal route length for the Berlin-Frankfurt am Main scenario is also only 4 km shorter than the road route, but with four transfers between road and rail (one last transfer not seen in the Fig. 2b is conducted in Frankfurt with a rest route length of only 2 km).

Even though the total route length can be shortened by multimodal routing, these routes are not reproduced in reality. One reason is that the test scenarios have been optimized considering only the length of the edges without any penalties in the connection edges to prevent excessive transfers. In practice, the transfer of goods is a costly and time-consuming operation and a multimodal route with multiple mode changes during short distances is unreasonable. Thus, choosing distance without further penalties for connection edges as a criterion for multimodal route search cannot be recommended. When optimizing for other criteria, the penalties and weighted edges are built so that the algorithm behaves in a more coherent way with realistic requirements. The results are presented in the following sections.



(a) Hamburg to Munich. (b) Berlin to Frankfurt am Main.

Fig. 2. Distance optimized multimodal routes using Dijkstra's algorithm compared to road only and rail only routes.

4.2 Performance Analysis Under Different Routing Criteria

After the performance of the algorithm is validated through the distance test, an analysis of its behavior when optimizing for different criteria is conducted. To do so, the algorithm has been applied to the same scenarios from Hamburg to Munich and from Berlin to Frankfurt am Main considering the three criteria cost, time and emission. All routes are generated considering 80 TEUs, i.e., one full load train, to be transported. The results of the optimization paths are presented in Table 10. Even though the length of the connection edges are presented in the table, the length itself does not influence the optimization for time, cost, and emission, as the weights of the connection edges are independent of the edge length. The length rather represents the physical distance between the closest rail and road nodes nearby the POIs.

For both scenarios, the algorithm behaves in a similar manner. When the route is optimized for time, a road only route is always chosen, since transferring goods is very time consuming and trains run much slower than trucks. One interesting fact that is observed is that the total route length for time optimization is longer than for distance optimization even though both produce only road routes. This can be explained by the fact that different speeds were assumed for highways and rural roads such that the fastest route is not necessarily the shortest.

On the other hand, for cost and emission, a multimodal route with mostly rail segments is preferred. This is due to the costs and emissions being much lower per TEU and km for trains. Subsequently, the routes found for cost and emission optimization are very similar as can be seen in Fig. 3. The slight differences

Table 10. Summary of route values for different optimization criteria.

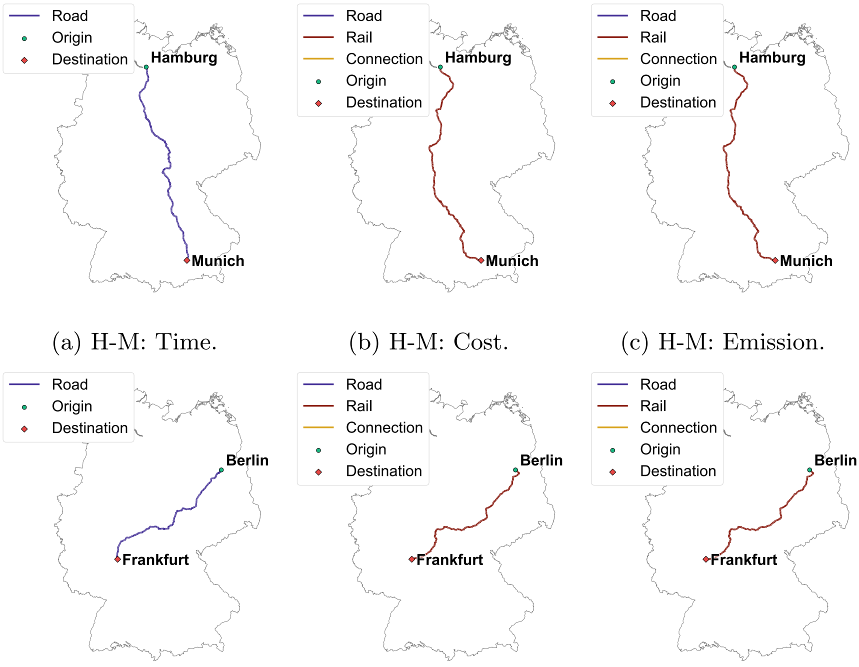
Scenario*	Optimization criterion	Section	Distance (km)	Time (h)	Cost (€)	Emission (t CO_2)
H-M	Time	Total	744.1	9.3	68,159.44	88.7
		Road	744.1	9.3	68,159.44	88.7
	Cost	Total	829.9	23.2	12,187.41	19.3
		Road	10.0	0.2	913.73	1.2
		Rail	818.4	14.9	3,273.68	18.1
		Connection	1.5	8.2	8,000.00	0.0
	Emission	Total	815.6	31.1	20,260.97	19.1
		Road	11.5	0.2	1,050.16	1.4
		Rail	802.7	14.6	3,210.82	17.7
		Connection	1.4	16.4	16,000.00	0.0
B-F	Time	Total	531.6	6.7	48,691.92	63.3
		Road	531.6	6.7	48,691.92	63.3
	Cost	Total	552.3	18.2	10,711.09	12.7
		Road	5.7	0.1	526.68	0.7
		Rail	546.1	9.9	2,184.41	12.1
		Connection	0.5	8.2	8,000.00	0.0
	Emission	Total	550.6	18.1	10,731.94	12.7
		Road	6.1	0.1	558.79	0.7
		Rail	543.3	9.9	2,173.15	12.0
		Connection	1.2	8.2	8,000.00	0.0

* H: Hamburg, M: Munich, B: Berlin, F: Frankfurt am Main

between the cost and emission optimized routes that can be observed in Table 10 are due to the selection of different connection edges near the destination. For emissions, the in total shorter routes are more beneficial, whereas for cost, taking longer rail routes even when the total route length is extended yields better results. Another feature that determines this slightly different behavior for cost and emission optimization is the penalty for switching modes. The costs of the emission case for Hamburg-Munich demonstrate this well as four transfers are conducted on this route even though the road part is only 11.5 km short.

Another observation that can be made is that the transfer costs shown by the 'connection' sections in Table 10 make up a large portion of the total costs in the multimodal transports. Thus, when considering shorter distances, the algorithm might choose to use only one mode of transportation. To test the behavior of the algorithm for shorter distances, an additional route between Berlin and Cottbus is investigated. The results are shown in Table 11 and Fig. 4. As expected, the algorithm yields a road only route for cost optimization as the transfer cost of 4,000 € is too high compared to the total road costs of only 11,490 €.

However, for emission optimization, the algorithm still chooses a multimodal route with two transfers. The different routes are clearly displayed in Fig. 4. Thus, for shorter distances, the choice between cost and emission has a large



(a) H-M: Time. (b) H-M: Cost. (c) H-M: Emission.

(d) B-F: Time. (e) B-F: Cost. (f) B-F: Emission.

Fig. 3. Distance optimized routes using Dijkstra's algorithm.

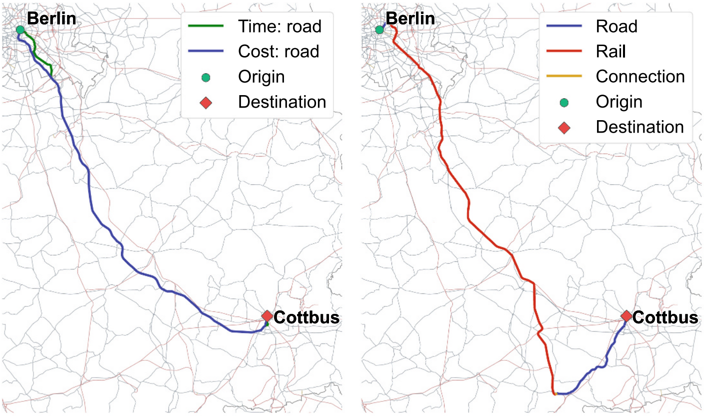
impact on the output of the algorithm while for larger distances similar results can be expected. Under our assumptions, the costs of the cost and emission optimized routes are very similar, but emissions are only halve for the emission optimized route. Therefore, even though economically the road only route is slightly favorable, ecologically multimodal transport is much cleaner.

Overall, the travel time of multimodal routes is much longer than that of the road only routes, which is expected as trains run slower than trains and the waiting and transfer time are relatively long for mode transfers. In real logistics, this can be a much bigger problem as trains and intermodal terminals are much less flexible than truck transportation. Especially for smaller quantities of TEU, resulting in less than full trains, scheduling and cost become more critical as availability is limited and cost increases when trains are not fully loaded. However, for large and repeatedly scheduled shipments, a transfer from road to multimodal transport can significantly reduce costs and emissions. To present more realistic routes, such aspects, especially for train shipments, should be considered in the route weights for costs and emissions. Another limitation of the current work is the proportional dependencies of the criterion weights on route length. In reality, costs and emissions per km decrease with larger distances. Thus, for a more realistic cost and emission analysis, fixed, time-

Table 11. Summary of additional scenario Berlin-Cottbus.

Scenario*	Optimization criterion	Section	Distance (km)	Time (h)	Cost (€)	Emission (t CO_2)
B-C	Time	Total	126.3	1.6	11,565.97	15.0
		Road	126.3	1.6	11,565.97	15.0
	Cost	Total	125.4	1.6	11,490.12	14.9
		Road	125.4	1.6	11,490.12	14.9
	Emission	Total	161.9	10.9	11,844.07	7.1
		Road	36.5	0.5	3,346.01	4.4
		Rail	124.5	2.3	498.06	2.7
		Connection	0.9	8.2	8,000.00	0.0

* B: Berlin, C: Cottbus.



(a) Time vs. cost. (b) Emission.

Fig. 4. Time, cost and emission optimized routes from Berlin to Cottbus.

dependent, and length-dependent parameters should be identified and included in the weight calculations.

5 Conclusion

In this paper, a route optimization methodology for Germany's multimodal freight network based on openly available data and graph-based algorithms was presented. OpenStreetMap proved to be a suitable data source for extracting road and rail networks, although some assumptions were required due to inconsistent labeling. The multimodal graph integrated both networks via intermodal stations, and edge weights were defined by distance, cost, time, and emissions. Using Dijkstra's algorithm, the method successfully generated feasible multimodal routes and was validated against a distance-optimized baseline. Time-based optimization favored road-only routes due to transfer penalties and lower train speeds, whereas emission-based optimization consistently favored rail. Cost-based optimization revealed that rail becomes advantageous over longer distances, while transfer costs dominate shorter trips.

The study demonstrates that graph-based approaches can capture the main trade-offs in multimodal route planning. However, several limitations remain. First, the current implementation relies on Dijkstra's algorithm. Alternative techniques such as the A* search algorithm or data preprocessing could significantly improve computational performance [6]. Second, the analysis focuses on optimizing a single criterion at a time and does not consider Pareto-optimal trade-offs or mixed-integer programming formulations. Third, operational aspects such as timetables, train occupancy, and parameter variations over long distances are not included, limiting the current model to an operational rather than tactical or strategic planning level. Future work will therefore focus on improving network data quality, refining weight parameters, incorporating timetable- and capacity-related logistics constraints, evaluating multi-objective frameworks, and extending the network to international corridors. These improvements will further enhance the robustness and applicability of multimodal route planning based on open data.

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Data Availability Statement. The code for this work is available at the following GitHub repository: https://github.com/lokkuz/multimodal-freight-routing.

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