TECHNO-ECONOMIC MODEL OF MULTIMODAL TRANSPORT

DAVID POUL, JIŘÍ GREGOR, MARTIN PAVLAS, YEE VAN FAN

Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czech Republic

David.Poul@vutbr.cz, Jiri.Gregor@vutbr.cz, martin.pavlas@vutbr.cz, fan@fme.vutbr.cz

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With the current effort to reduce transport emissions, the shift in the transport of goods from road to rail or combination is expected on a larger scale. For this shift to have the expected results, it needs to be supported by detailed project planning and calculation. The paper presents the techno-economic model of multimodal transport, focusing on road and rail transport. The model includes a vast database of transport systems for both types of transport. To complete the logistic chain, the model includes the calculation for transfer stations, handling equipment, and other needed parts. The model also includes an economic evaluation allowing analysis of the whole logistic chain of multimodal transport or performing the comparison of individual types of transport.

Keywords:
techno-economic model,
multimodal transport,
rail transport,
road transport,
intermodal systems,
transfer station,
circular economy

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1 Introduction

The current state of computational support of multimodal transport is insufficient. Models are simplified and do not always include all important parts of the logistics chain. One can often come across models that are not connected to real infrastructure and using only parameter for distance without considering e.g. slope or different route class (Jiang J. et al 2020) or include only general types of transport systems (Jiang C. 2022) which is not possible to modify without changing the calculation. Many simplifications result in inaccuracies that affect the evaluation quality. It is also necessary to distinguish between models that focus on mathematical optimization versus models that focus on technical-economic evaluation. The first-mentioned models, i.e. models or modelling approaches focusing on mathematical optimization, can be found more often in the literature. Techno-economic models are difficult to find on the level that is detailed enough for the universal use case.

In terms of multimodal transport, the models very often focus on the evaluation of emission production, especially CO_2, when comparing individual types of transport (Kirschstein, Meisel 2015) and not cost evaluation. If the models consider cost evaluation, their frequent shortcoming is only a simplified calculation, i.e. consideration of constant values of transport costs for individual modes of transport independent of the route, often given in the unit [€/tkm] (Christensen, Labbé 2015). This is addressed (Gregor, Šomplák, Pavlas 2017), which considers individual factors (vehicle type, consumption, route, loaded weight, etc.). As a result, compared to the previous approach, transport costs are not constant, but a variable value defined by different parameters.

(Niérat 2022) deals with the comparison of road and intermodal transport from the Dutch ports of Dunkirk and Zeebrugge to Dusseldorf and follows on from article (Hintjens et al. 2020). The authors make a critical reflection on some decisions and assumptions - overestimation of the intensity of traffic, underestimation of the costs of the intermodal chain - which in the compared article leads to a more significant decrease in the costs of intermodal transport compared to road transport. On the contrary, in the following article, intermodal transport is only a few percent cheaper than the purely road variant - this is due to the inclusion of the costs of transshipment of containers in the port, the transfer from road to rail transport and, above all, the inclusion of costs for the last section of the journey - transfer from rail to road transport and delivery of cargo to the destination within the urban agglomeration – this final transfer was completely omitted in the referenced article. Here it's noticeable how important it is not to neglect the individual steps of the logistics chain, which can subsequently lead to a significant advantage of a certain type of transport. In terms of the model, simplifications were considered in both articles – the costs were determined on an annual basis and for a specific transport system – so one cannot speak of the universality of the model.

As it follows, a minimum of articles, models, or tools are devoted to complex multimodal transportation from the point of view of cost and technical evaluation. Probably the most overlooked part of the models is the transportation system specification, which is mostly generic, with no possibility of variability for the needs of the user. This problem occurs especially in the case of rail transport, which is evaluated rarely in the mentioned models and, if so, its specification lacks more detailed parameters. A critical feature of the models is the inclusion of all parts of the logistics chain – if even small parts are omitted, the results may be distorted, which may favour a certain type of transport. Therefore, creating an advanced techno-economic model of multimodal transport, which can evaluate in detail the technical, economic, and environmental demands of a given logistic chain is required.

2 Techno-economic model

The work aims to create a universal techno-economical model of multimodal transport (i.e. "TE model") with a focus on road and rail transport. Other modes of transport can be added if needed. The model in main form is created for users with basic knowledge of logistics but it also supports going deeper into the details if users have the knowledge to set the model correctly. The model can evaluate the whole chain as well as individual parts of the logistics chain so it can also be used for comparing different scenarios or individual types of transport.

The research showed key areas which the model should consider. Those areas are:

- Wide database of transport systems for road and rail transport
- Inclusion of all key parts of the logistics chain

- Infrastructure network based on real infrastructure
- Determination of the theoretical consumption of the transport system
- Determination of relevant elements for the evaluation of emission production (CO_2, NO_X, solid particles, etc.)
- Detailed assessment of technical and economic parameters

The model supports the use of two main types of transport – intermodal transport where the goods are loaded in a single transport unit for a whole transport so there is no manipulation with goods as itself (e.g. intermodal container is used) and "classic" type of transport when it is necessary to handle the goods every time in case of changing the transport mode.

The user will be able to evaluate the current situation (e.g. the use of purely road transport) and the newly proposed one, where it will be, for example, the use of multimodal transport for transport from point A to point D. The example will be shown for waste transport. After collecting the waste in point A, the road transport will be used to point B, where the waste will be transferred into an intermodal unit and then loaded onto a railway wagon. Rail transport will be used from point B to point C. The last step will be to transfer it to a road vehicle again and from point C to point D road transport will be carried out. The transport scheme is in Figure 1.

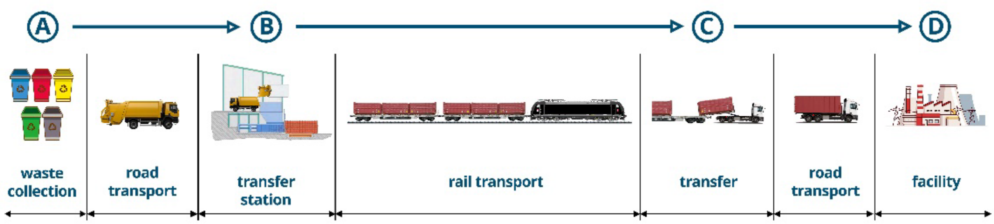

Figure 1: The example scheme of multimodal transport
Source: own

The model is composed of sub-models that include:

- Road transport
- Rail transport
- Transfer station
- Handling equipment

Transshipments between different modes of transport are a key part of the logistics chain. The transshipment can be done simply with the use of handling equipment on the paved area, e.g. next to the track at the railway station. When transferring a large volume of goods frequently with adjusted the entire system, it is worth using a stationary transfer station. Most often it's done for transshipment of intermodal containers.

A wide range of different transshipments can be encountered within the logistics chain. It is, therefore, necessary to focus on individual aspects that are important for the given transshipment. For example, the transfer of bulk materials using a wheel loader has significantly different technical specifications and costs than the transfer of liquid components from tanks or the use of a stationary transfer station for transferring containers.

Due to the scope of the article, the sub-models for transfer stations and handling equipment will not be analysed in detail in this article. The focus will be mainly on road and rail transport.

The main sub-models are the ones for road and rail transport. Both models are created with the same structure and layout so it's user-friendly. Both models are also designed with the same input and output parameters. This ensures the possibility of easy connection of both models and the possibility of easy comparison of both types of transport. The structure of both models is shown in Figure 2.

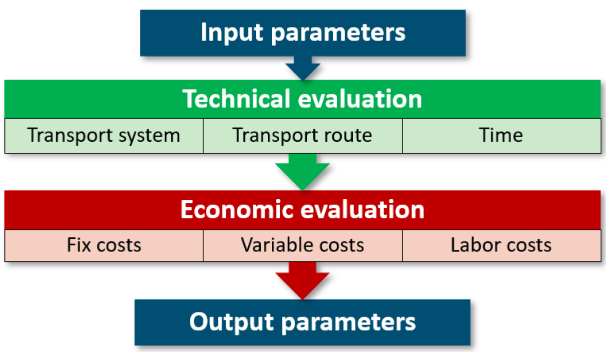

Figure 2: Structure of sub-models

Source: own

The models have numerous input parameters, e.g. the sub-model for road transport has 98 parameters and the one for rail transport more than 110. Many of those parameters are based on research and it's not necessary to change them often. But it's still possible because they affect evaluation. Also number of parameters is changed automatically based on a selection of the transport system or pre-set data or limits. The key input parameters are:

- Starting point
- Destination point
- Type of transport system
- Bulk density or transported weight per cycle [kg/m^3, t]
- Transported weight per year or weight which is needed to be transported [t/year, t]

Main output parameters are:

– Total annual costs	[€/year]
– Cost of 1 ton	[€/t]
– Costs per 1 tonne-kilometre	[€/tkm]
– Number of cycles per year	[-]
– Theoretical utilization of the transport system	[%]
– Annual mileage	[km/year]
– Reworked weight in one cycle (loaded weight)	[t]

2.1 Integration to the optimization tools

The model can be integrated into optimization tools. It is possible to use it as a whole, i.e. with a complex detail, but this increases the computational requirements, which is not desirable in most cases. Otherwise, the model can be simplified by setting aside selected parameters that will change for the task and consider the rest of the parameters as constants. Subsequently, the entire model is reduced to one equation.

The model also be used for pre-processing or post-processing. The typical approach can be:

- pre-calculations by TE model (e.g., all routes combinations - price, time, etc.) – input to optimization task
- optimization task (e.g., position of transfer stations and necessary supply routes)
- refinement of the output from the optimization task with use of TE model

3 Database of transport systems

Defining the transport system is an important part of the model. Since the model is universal, the database for road or rail transport includes a variety of different elements from which the final transport system can be set up. An important note is also that users can add elements of the transport system to the database.

The database for road transport considers:

- Passenger car
- Van
- Semi-trailer tractor
- Rigid chassis
- Semi-trailer
- Trailer
- Container
- Custom rigid cargo bodies

The database for rail transport considers:

- Locomotives
  - Electric
  - Diesel
- Goods wagons
  - Flat/intermodal wagon
  - Open/covered wagon
  - Tank wagon
- Intermodal containers

Each of the parts listed above includes many different real types with technical parameters given by product lists or companies. For example, each of the locomotives in the database is not only defined by general parameters such as weight, number of axles, etc. but also has given a traction characteristic (Figure 3) with which the model calculates.

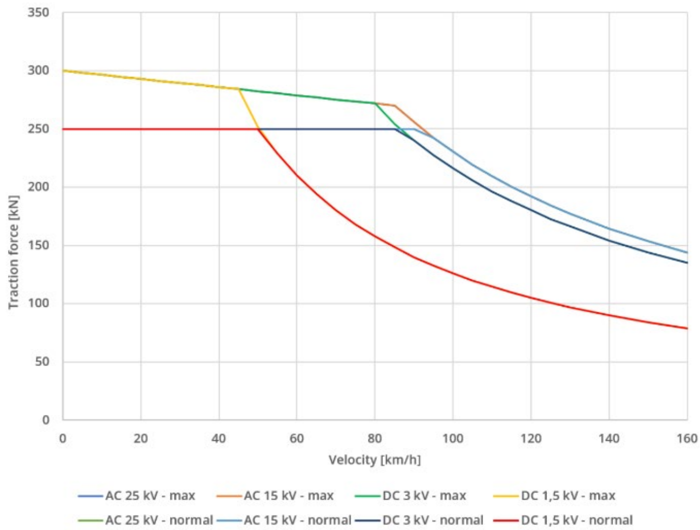

Figure 3: Traction characteristics of Siemens Vectron locomotive
Source: own based on Siemens's product list

The database makes it possible to select individual parts of the transport system and to assemble the final one in a modular way so it means that every different setup will have different parameters such as empty weight, different possible payload, each locomotive has different traction characteristics, power and so on. This guarantees that the model will calculate with accurate data. In terms of intermodal transport, i.e. intermodal containers, the database currently contains ISO containers, Innofreight system and ACTS system (Abroll Container Transport System).

4 Infrastructure network and route evaluation

Infrastructure is based on real data for both road and rail transport. Currently, the model includes infrastructure for the Czech Republic but it's possible to add other countries (and update the model with the specifics of operation in the given country).

However, since both types have their specifics, the next chapters will describe infrastructure in more detail.

4.1 Road transport

Road infrastructure is quite complex. Since the main focus of the model is for freight transport and not all roads are passable for trucks, it was possible to reduce the complexity of the network. All municipalities (6,254) can be considered as a benchmark. After proper evaluation, the smallest municipalities were taken out and the points of interest were added (Waste-To-Energy power plants, landfills, large production complexes outside the municipalities, etc.). With that, the database contains 1,132 points.

The real network was reduced with the condition that it's possible to connect all those points for different categories of vehicles. However, there are points where it's not possible to get by some categories of vehicles (large vehicle/truck) because there is some barrier (load capacity of the bridge, low underpass height). The categories were based on weight and size:

- Category 0: passenger car
- Category 1: max 3.5 t, max 2.5 m
- Category 2: max 10 t, max 3.2 m
- Category 3: max 26 t, max 4 m
- Category 4: max 48 t, max 4 m

The output network consists of 230,835 sections which respect intersections, turns, etc. Each section is defined with multiple parameters such as length, route class, slope, if there is tunnel or bridge, etc. As Figure 4 shows, the network is still quite complex and detailed.

Since the infrastructure considered in the model is not 1:1 with real infrastructure, the route evaluation in the model allows the user to add e.g. the last section from the destination point based on the network (the added section is defined only with length) and thus make the calculation more precise. The model also allows ignoring included infrastructure and defining the transport route manually based on length for each route class.

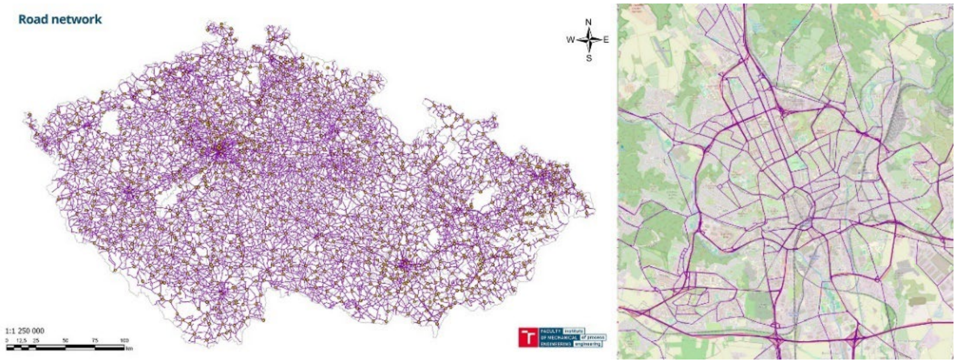

Figure 4: Road infrastructure

Source: own

A sample evaluation for different categories of vehicles is shown in Figure 5. It's noticeable that there are barriers for higher categories, and it is therefore necessary to use a different transport route, usually a longer one, which leads to different results in the overall evaluation.

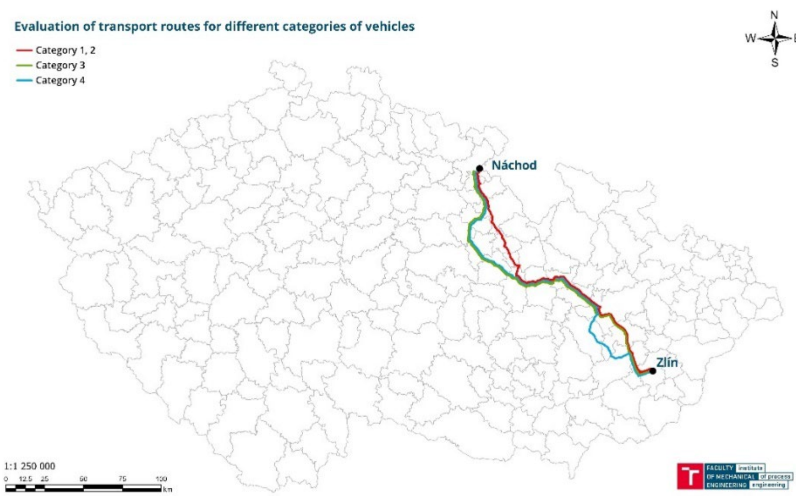

Figure 5: Evaluation of transport routes for different categories of vehicles

Source: own

It is also possible to evaluate route with multiple segments or circular route (Figure 6, Figure 7). The load factor can be different for each segment allowing to calculate loading/unloading at multiple stops.

Figure 6: Circular route
Source: own

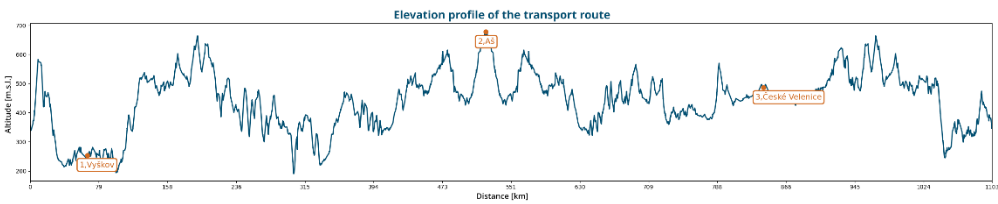

Figure 7: Elevation profile of the transport route
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4.2 Rail transport

Since the rail infrastructure is not as complex as the road one, the model incorporates full real infrastructure. The only limitation for now is that the double track is considered a single track. In some sections, this can make a difference in a different speed profile in the curves on each track. However, this should be addressed in the next update of rail infrastructure considered in the model.

The rail infrastructure includes 2,755 points with 4,118 sections. This apparently low number is due to the original division of the individual interstation sections with regard to the slope of the track, not the individual curves on the track. As it was mentioned before with a number of tracks, this should be addressed as well in the next update of infrastructure. Each section has 28 parameters that the model can use for the calculations, such as the length of the section, maximum speed, road class, normative length of the train, etc. Rail infrastructure is in Figure 8.

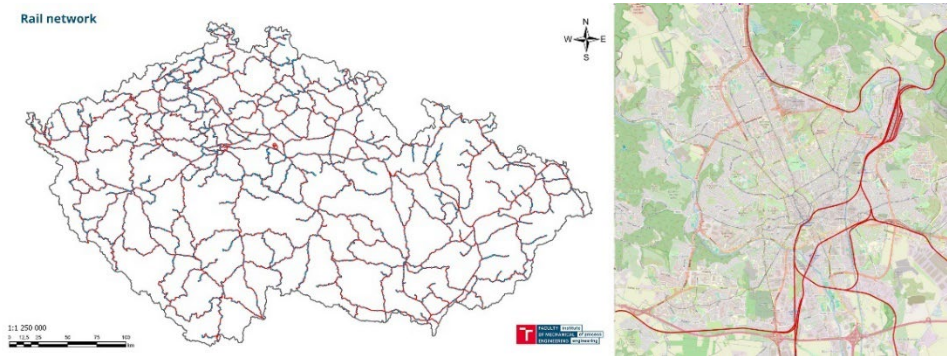

Figure 8: Rail infrastructure

Source: own

Based on the defined transport system, the model will evaluate the limiting parameters and conditions (length of the train, axle load, traction power of the locomotive, etc.). The user can also limit some sections of the infrastructure, for example, due to the closures. Then the model will find the best transport route based on the conditions.

Part of the evaluation is the calculation of speed profile and energy/fuel consumption. This calculation considers multiple parameters such as the traction characteristics of the locomotive, load of the train, slope of the track, multiple resistances of the train, etc. The calculation is quite complex and again, due to the scope of the article, it won't be described in detail. The sample evaluation of the speed profile is in Figure 9, force diagram in Figure 10. Calculated consumption is in kilowatt hours [kWh] or litres [l].

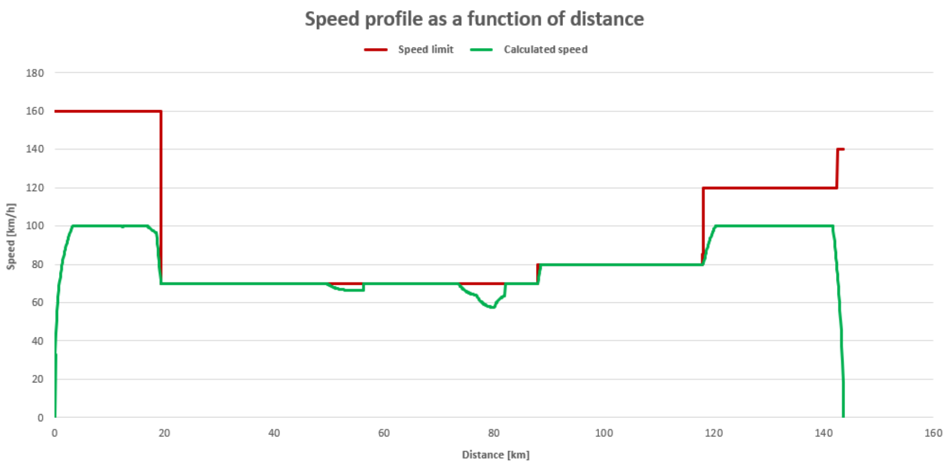

Figure 9: Speed profile as a function of distance

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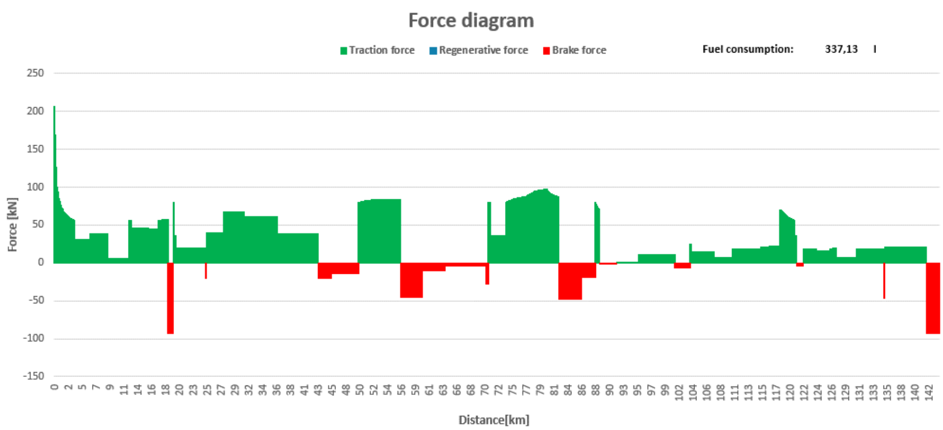

Figure 10: Force diagram, source: own

Source: own

Since the model and rail infrastructure do not consider curves on the track it's noticeable that in the speed profile, there are no drops in speed caused by lower maximum speed in curves (there are speed drop caused by slope of the track). It's going to be addressed in the next update of infrastructure with higher detail.

5 Emission production

The production of emissions is an often talked about topic these days. There is a significant effort to reduce produced emissions, as transport is a significant air polluter and there are many ways to calculate emissions production. The one which is used in the presented model is based on fuel/energy consumption calculated by the model and values of emission factors given by „EMEP/EEA air pollutant emission inventory guidebook 2023" published by the European Environment Agency (EEA), an agency of the European Union. An example of emission factors given by the guidebook is in Table 1 for NO_X and Particulate matter (PM). Emission production for CO_2 is given by the combustion equation, respectively the emission factor for the fuel.

Table 1: Emission factors for NO_X and PM

Vehicle category	Fuel	NO_X [g/kg fuel]			PM [g/kg fuel]		
		Mean	Min	Max	Mean	Min	Max
Passenger car	Petrol	8,73	4,48	28,89	0,03	0,02	0,04
	Diesel	12,96	11,20	13,88	1,10	0,80	2,64
	LPG	15,20	4,18	34,30	0,00	0,00	0,00
Light commercial truck < 3,5 t	Petrol	13,22	3,24	25,46	0,02	0,02	0,03
	Diesel	14,91	13,36	18,43	1,52	1,10	2,99
Heavy duty vehicle > 3,5 t	Diesel	33,37	28,34	38,29	0,94	0,61	1,57
	CNG	13,00	5,5	30,00	0,02	0,01	0,04
Motorcycle	Petrol	6,64	1,99	10,73	2,20	0,55	6,02

Source: https://www.eea.europa.eu/publications/emep-eea-guidebook-2023/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view

6 Economic balance

Before describing the costs, it is important to mention the time component of the entire evaluation. Based on the evaluation of the transport route, the time that the given transport will take from start to finish is determined - loading, transport, transhipment, further transport, unloading, etc. This time can be compared with the working time of the entire transport system in one day or a whole year. Thanks to this, a percentage representation of the evaluated transport to the total working time is calculated. This parameter can be described as the theoretical utilization of the transport system and it's important for the calculation of economic balance.

Costs can be divided into fixed and variable costs. Labour costs are set aside. Fixed costs are mainly the costs of purchasing or renting transport systems, their maintenance (annual technical controls, regular and irregular maintenance) and insurance together with road tax. Maintenance costs are set at a fixed amount per year - assumed regular maintenance or they can be evaluated based on total mileage which is nowadays quite typical in rail transport.

The model also considers the lifespan of each part of the transport system. For example, the typical lifespan of a semi-trailer truck is around 6-7 years, locomotive around 30 years. During the expected lifespan of the project under consideration, e.g. 20 years, the company will need to buy a new truck three times. The locomotive only once with the possibility of doing larger modification at half of the lifespan. Those differences for each transport type are considered in the model and are evaluated for each part of the transport system.

Variable costs include tolls and fees, tire costs based on annual mileage and operating costs. The toll fee is determined based on road class and toll sections. The biggest part of variable costs are operating costs. These are mainly determined by the consumption of fuel or electricity (rail transport), oil and AdBlue liquid, which is necessary to reduce emissions from exhaust gases. In the case of rail transport, these are also the costs of the transport route (similar to a toll) but are paid on the entire railway network.

The last big part is labour costs. These are considered on a simplified approach. Labour costs for the crew play a primary role. The remaining labour costs (administrative and operational overheads) are considered constant but can be developed based on more detailed information.

The economic balance considers several other parameters. Costs can be evaluated for the purchase or rental of transportation systems and their use only for evaluated transportation. The second option is the evaluation of costs based on the theoretical utilization of the transport system, which enables the percentage expression of costs to be determined with regard to the time required for the evaluated transport. With this approach is possible to combine multiple evaluated transports for one transport system.

6 Case study

The output of this article is a conference poster describing the main characteristics of the model, its usage and incorporating the model into optimization tasks. Thus, the presented study case is described briefly.

The presented model was used to design and evaluate the logistics chain for supply of heating plant in Olomouc which aimed to switch from coal to a mixture of biomass (20 kt/year) and alternative solid fuel (RDF) (80 kt/year). As part of the evaluation, suitable transport systems were proposed, for which theoretical breakpoints were determined. Figure 11 shows a comparison of road and rail transport for the transport of 20 kt/year of biomass and 80 kt/year of RDF. Due to the significantly larger quantity (and also bulk density, thus higher weight) in the case of RDF, rail transport has a lower price than road transport from 280 km as opposed to 490 km in the case of biomass.

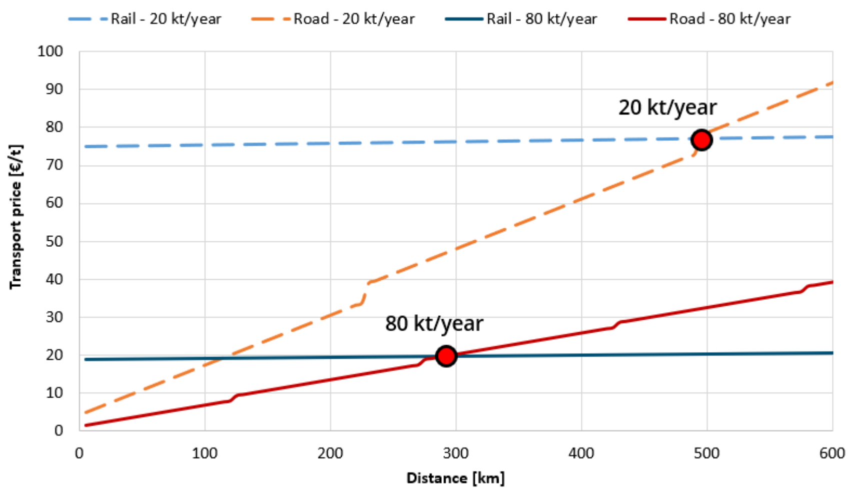

Figure 11: Theoretical breakpoints

Source: own.

Furthermore, localities with sufficient production of both commodities were selected and an evaluation was carried out for road and rail transport. Two main scenarios (1 – biomass from single location, 2 – biomass from 4 locations) were further divided into two variants in terms of locations of producers. Variant 1 was carried out fully by rail transport, in variant 2 rail transport was used for RDF and road transport for biomass.

- 1a – RDF: Bielsko-Biala (Poland); biomass: Ždírec nad Doubravou
- 1b – RDF: Linz (Austria); biomass: Ždírec nad Doubravou
- 2a – RDF: Bielsko-Biala (Poland); biomass: Doloplazy, Bouzov, Vsetín, Otaslavice
- 2b – RDF: Linz (Austria biomass: Doloplazy, Bouzov, Vsetín, Otaslavice

Table 2 shows the resulting prices of the entire logistics chain for each variant. The cheapest option is option 2a, where RDF is transported from Bielsko-Biala (rail transport) and biomass is transported from 4 regional locations (road transport).

Table 2: Transport prices of individual variants

Variant	Price [€/t]
1a	20,2
1b	20,85
2a	19,83
2b	20,48

7 Conclusion

The techno-economic model presented in the article aims to focus on problematics in detail and addresses many areas which are insufficiently covered in models presented in current research. The model can be used to evaluate a wide range of transports, both from the point of view of the carrier and from the point of view of the contracting authority, which wants to know the costs of transport before starting negotiations with carriers.

Another use of models is in combination with optimization tools, where the techno-economic model can be used for pre-processing, or to refine the results of given optimizations. It can also be simplified and directly integrated into the optimization tool and help with the precision of optimization right away.

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References

Jiang J., Zhang D., Meng Q., Liu Y. (2020). Regional multimodal logistics network design considering demand uncertainty and CO2 emission reduction target: A system-optimization approach, Journal of Cleaner Production, 248, doi: 10.1016/j.jclepro.2019.119304

Jiang C. (2022). Research on Optimizing Multimodal Transport Path under the Schedule Limitation Based on Genetic Algorithm, Journal of Physics: Conference Series, 2258, doi: 10.1088/1742-6596/2258/1/012014

Kirschstein T., Meisel F. (2015). GHG-emission models for assessing the eco-friendliness of road and rail freight transports, *Transportation Research Part B: Methodological, 73*, 13-33, doi: 10.1016/j.trb.2014.12.004

Christensen T. R. L., Labbé M. (2015). A branch-cut-and-price algorithm for the piecewise linear transportation problem, *European Journal of Operational Research, 245*, 645-655, doi: 10.1016/j.ejor.2015.03.039

Gregor J., Šomplák R., Pavlas M. (2017). Transportation Cost as an Integral Part of Supply Chain Optimisation in the Field of Waste Management, Chemical Engineering Transactions, 56, doi: 10.3303/CET1756322

Niérat P. (2022). Methodological shortcuts in intermodal freight transport: Critical review and proposals, *Journal of Transport Geography, 103*, doi: 10.1016/j.jtrangeo.2022.103396

Hintjens J., Van Hassel E., Vanelslander T, Van de Voorde E. (2020) Port Cooperation and Bundling: A Way to Reduce the External Costs of Hinterland Transport, *Transport Systems for Sustainability: Policy, Planning and Exploitation, 12*, doi: 10.3390/su12239983