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Transportation Cost as an Integral Part of Supply Chain Optimisation in the Field of Waste Management

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This paper deals with transportation cost modelling in the field of waste management. Waste transport from producers to the pre-processing facilities and/or plants for final treatment significantly contributes to overall processing cost and should be properly investigated to select the most convenient solution. The main goal of this paper is to describe comprehensive techno-economic model involving several types of transportation systems (for example collecting vehicles, transfer stations, intermodal container system). Each transportation system has been analysed according to its specific parameters that is transport distance, amount of waste transported, etc. The results of the calculation (for example specific cost per ton and kilometer) then serve as inputs for detailed supply chain optimisation involving complex networks. Correct implementation of transportation cost with relation to other system key parameters (for example distance, capacity of waste) enables getting more reliable output data. In the paper, authors described methods of optimisation task simplification without losing exactness of real solution. The impact on computational time will be addressed and concrete results related to real industrial case study in the field of waste-to-energy is presented.

1. Introduction and Motivation

Transportation and complex transport networks in general have become an integral part of every aspect of our lives. Major task to solve in transportation and supply-chain management is the interconnection of all the elements involved so that the economically most viable solution with minimum environmental impact and competitive price may be found. Various modifications of the so called network-flow models and/or supply chain models are commonly employed to optimise the solutions. Waste management and especially transport of specific types of waste for their material or energy utilisation represent a promising area, where advanced integrated logistic models are needed (Bing et al., 2016). Both strategic and tactical issues must be addressed here (Ghiani et al., 2014).

NERUDA, software first introduced by Šomplák et al. (2014), represents a competent tool for complex solution to waste management tasks. NERUDA resolves transportation tasks, and simulates competitive environment with various facilities operating in a given area. NERUDA has been proven by several practical applications in the Czech Republic (Zavíralová et al., 2014). However, it is an open tool ready to be applied at an international level. Transportation network itself and transport cost (Golecha and Gan, 2016) associated with this network and quantity of waste transported represent important input parameters for any calculation carried out by NERUDA (Šomplák et al., 2015). Constant transport cost (for example unit cost per tonne and kilometre) is considered as current state-of-the-art to avoid complex task and excessive computation time.

Partial results of the complex analysis of transportation cost will be presented further in the paper. The paper will further illustrate deviations which occur if costs are considered to be fixed. Recommendations for application of complex models for supply chain models will be also presented. Results can motivate advancement of current optimisation models in future.

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2. Transportation Network System

Figure 1 illustrates a basic overview of transportation systems that are common in waste management. Road transport is the primary type of transport, and will be fundamental for waste transport over short and medium distances. And yet, rail transport is a significant player in countries with developed waste management thanks to its low environmental impact. Rail is especially favoured for transport over long distances thanks to its economic benefits.

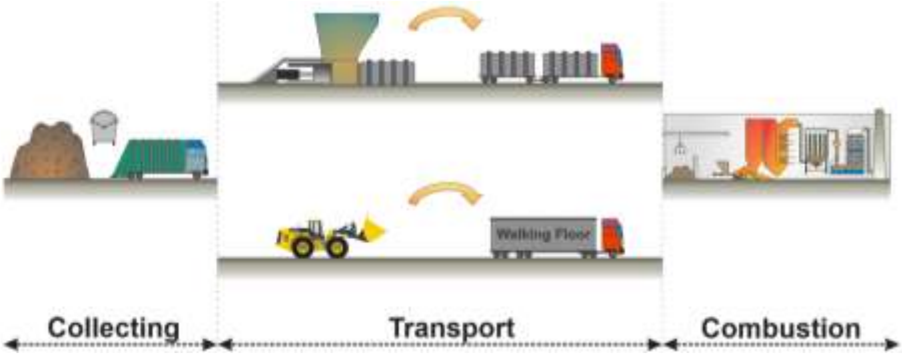


Figure 1: Transportation network system: special focus on road transport

Three transport systems specified below are among the basic waste transportation networks:

- Garbage trucks and direct transport to the nearest landfill site, transfer station or treatment plant.
- Garbage truck + transfer station with press equipment + vehicle with containers and pressed waste.
- Garbage truck + transfer station + handling equipment + vehicle with Walking Floor semitrailer + non-pressed waste.

Each system has its benefits and drawbacks. In this respect, a typical task here, the so called allocation problem, is to propose the optimum solution to the transportation network system, collection sub-area and transfer stations, and design of their capacities. As will be demonstrated later on, direct transport of waste in garbage trucks is effective only for short distances. In other cases, container systems or high-capacity trucks perform better. The advantage of pressed waste system is the fact its capacity is approximately by 25 % bigger than capacity of the non-pressed waste system. However, legislation restrictions must be considered (weight limit for road transport in the Czech Republic is 48 t; standard weight limit in the EU ranges from 36 % to 48 t). The Czech Republic is among European countries with the highest admissible weight limit for road transport.

3. Analysis using Techno-Economic Models

In order to perform relevant analysis, advanced techno-economic models have been developed. These models include all necessary inputs and information about every element of the system (truck, garbage truck, transfer station etc.). Figure 2 shows an example.

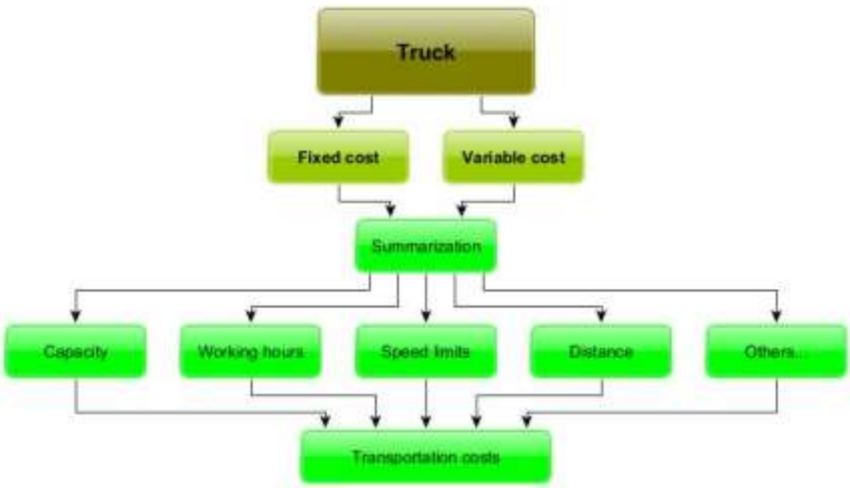


Figure 2: Structure of technical-economic transport model

Model inputs include especially basic technical information about vehicle, and operational and investment costs. Fixed and variable annual costs are calculated from these inputs. Annual amount of transported (processed) waste and the transport distance are important parameters in the model. These two parameters help identify the total transport price for both options, that is EUR/km.t and EUR/t. In addition to the transport price, the model further helps find out how many vehicles are necessary in relation to working time, transport capacity and transport distances. Speed limits and an average transportation speed, defined for particular road classes, are also important features in the transportation models. Differences between movement through cities, residential areas and, on the other hand, through free countryside should be taken into account too.

3.1 Garbage trucks

Garbage trucks make up an essential part of the waste management system. Garbage trucks are expensive and their main purpose should lie in waste collection from the producers. The waste transport itself must be adapted to very short distances to processing sites and/or transfer stations. Waste from producers is collected on the door-to-door basis within the so called kerb-side collection system. Alternative collection systems, such as high-volume containers that make rather costly collection much less expensive, are available only occasionally. High-volume containers most of all reduce labour costs, which are a dominant part of costs associated with garbage trucks operation. Quantification of labour costs is given in Table 1. For example, we can mention automatic waste collection vacuum systems (MetroTaifun - Automatic Solid Waste Collection), which are among the progressive systems using high-volume containers.

Table 1: Comparison of labour costs for garbage trucks and hook-lift trucks

Garbage truck		Lorry for high-volume containers	
Number of workers	Monthly wages	Number of workers	Monthly wages
1 × driver	900 EUR	1 × driver	900 EUR
2 × serviceman	725 EUR	-	-
Monthly costs	2,350 EUR	Monthly costs	900 EUR

For presentation of results, the following universal type of a garbage truck with the following parameters was considered:

- Garbage truck (tri-axle vehicle, 9.5 t of waste, linear press, HALLER X-2C M-2T).

The techno-economic model was developed using real-operational data to create the whole calculation and relevant simulations. It is important to distinguish between collection phase and transportation, where the capacity of the truck is full and the waste is shipped to the disposal facility. It has been discovered that the average movement speed of the garbage collection trucks is their key parameter. The average movement speed is the speed comprising the speed of waste collection and speed of following transport of the waste to the transfer station, or a waste-to-energy facility and back. Estimate of the speeds is a result of long-term statistic processing of information about real movements of the vehicles. There are differences among speeds of the vehicles in the cities, villages and mixed-use zones. The most variable speed is in city areas since the speed there depends on traffic jams and the so called green wave (synchronised traffic lights).

Figure 3 presents basic results for garbage trucks. For presentation of the results, uniform working time of 8 h, and two low average speeds of 8 km/h and 15 km/h were selected for short distances especially in city infrastructure as shown in Figure 3(a). Transportation cost for longer distances and higher average speeds (30 km/h and 50 km/h) are given for comparison as shown in Figure 3(b). Quantification of transportation cost is conducted for an annual transport capacity of 60 kt.

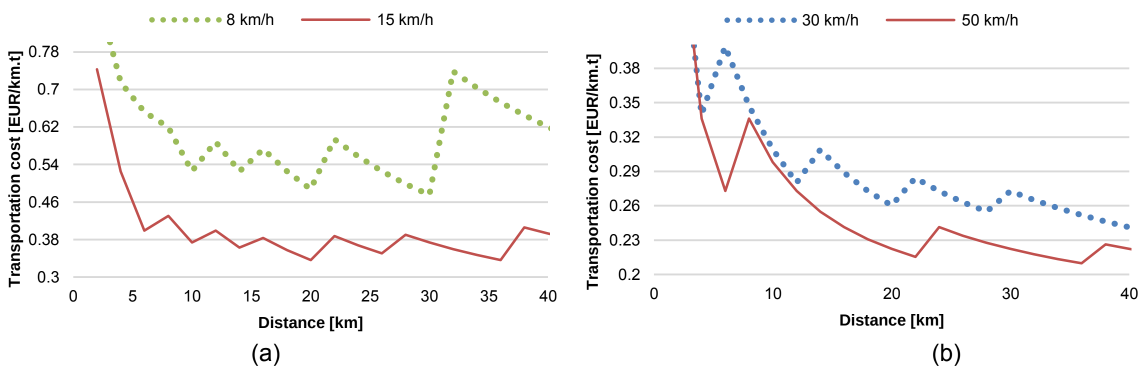


Figure 3: Transportation cost for various average speeds and annual capacity of 60 kt

3.2 Vehicle Systems

In this part of the paper, evaluation of the waste collection costs is given. This means evaluation of costs after the waste is transferred from the garbage trucks to transfer stations, and then, based on a given type of transportation solution, committed to a particular vehicle system. The resulting cost is subject to annual amount of waste.
Two following scenarios were analysed in order to select a suitable type of a vehicle:

- A1: Pressed waste (bulk density: 407 kg/m^3)
- A2: Non-pressed waste (bulk density: 275 kg/m^3)

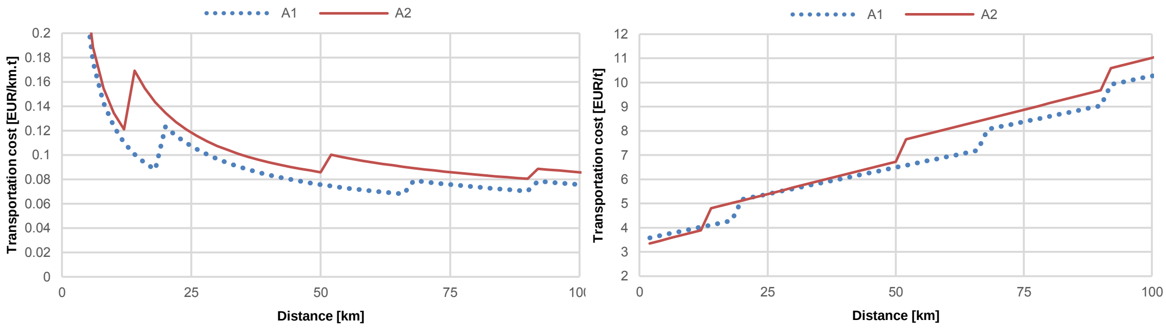
Two basic types of automobiles were considered:

- A1: A vehicle system with a lorry and a tri-axle trailer: transport of two 30 m^3 containers.
- A2: A vehicle system with a puller and a Walking Floor system: a special 90 m^3 semitrailer with a sliding floor (considered effective working space of 75 m^3).

Further, it is necessary to state basic information about the weight of the vehicle in running order and service weight of the vehicle system; these are given in Table 2 and they are key parameters in application of legislative restrictions. In case of the vehicle with pressed waste, 48 t per vehicle is the limit valid for the Czech Republic. Differences in amount of transported waste depend on waste bulk density and use of the semi-trailer volume in the walking floor system.

Table 2: Weight parameters of the vehicle systems

Network type	Automobile	Trailer/Semi-trailer	Container	Amount of waste	Total
Pressed waste	12 t	4.5 t	2 × 3.5 t	24.4 t	47.9 t
Non-pressed waste	10 t	7.8 t	-	20.7 t	38.5 t



(a) (b)

Figure 4: (a) Quantification of transportation cost of A1 and A2; (b) Cost quantification of A1 and A2, including transfer of the waste

Figure 4 illustrates quantification of transportation cost for pressed and non-pressed waste; the average speed considered for both systems is 60 km/h. Figure shows specific details with breaking points that clearly demonstrate time when new vehicles need to be purchased. The breaking point for non-pressed waste occurs earlier due to smaller amounts of transported waste. It is worth noting that both systems have a breaking point at around 90 km distance, and new lorries should be purchased. The reason is that the lorries can no longer do more cycles per day within the given working time. To up to 100 km distance, the amount capacity of waste is very important parameter. If the amount of collected waste rises, more and more lorries have to be purchased both for A1 and A2 systems due to long waste distances of one cycle. If we compare A1 and A2 systems only in terms of operating costs, the A1 system is always more economical and profitable. This is a result of large transportation capacity. The same reasoning applies to any type of a system with a specific capacity.
Analyses prove that costs of the waste collection up to ca. 50 km distance are roughly similar for both systems. But then, the A2 system becomes more costly. The effect is even more pronounced with a higher distance.

3.3 Results exploitation for improved network flow models

Quantification of the transportation costs was tested for a real transport network in the Czech Republic with a total of 206 transport nodes representing 206 municipalities with extended powers. Complex analysis revealed the following conclusions:

- There is a significant dependence on transportation distance and amount of waste. The same dependence which applies to dependence on distance and fixed amount of transported waste is noticeable for constant distance and variable amounts of transported waste - Figure 5(a).

- Garbage trucks should be purposefully utilised for quick collection of waste and its transport to the nearest processing facility.
- If the distance is longer than ca. 20 km, it is worth considering transfer stations with a waste press system. The breaking point depends on amount of transported waste; siting and capacity of the transfer station must be a result of optimisation.

The above-discussed NERUDA tool optimises waste flows between producers and processors in a given territory. Among others, model of a road transport infrastructure represents a key input. The simplest network is made up of only edges that connect the nearest points. On the other hand, we have a complete graph with paths among all nodes. If the distance between any two nodes is known this is an advantage of complete graphs. Computational complexity, caused by many variables involved, is a disadvantage. Another important input is transportation cost relevant to every edge. If authors are considering a constant price (EUR/km.t), it may be a gross simplification that could affect results of the optimisation. Therefore, the authors analysed potential implementation of the above given price models. Difficulties with quantification of the transportation costs arise from transport of waste along particular edges. Amount of waste transported on each edge is a result of optimisation, and transportation costs are a variable function (see Figure 5(a)). Each edge in a complete graph may be assigned a function similar to the one in Figure 5(a). Its saw-like shape might refer to mix integer non-linear programming; this solution is not real. More complex and extensive tasks would call for heuristic methods. To keep the task practically applicable with reasonable demand on computing time, the cost function has to be linear and/or linearised. An example of linear model for particular edge with distance 90 km obtained using least square method is presented in Figure 5(a) and 5(b).

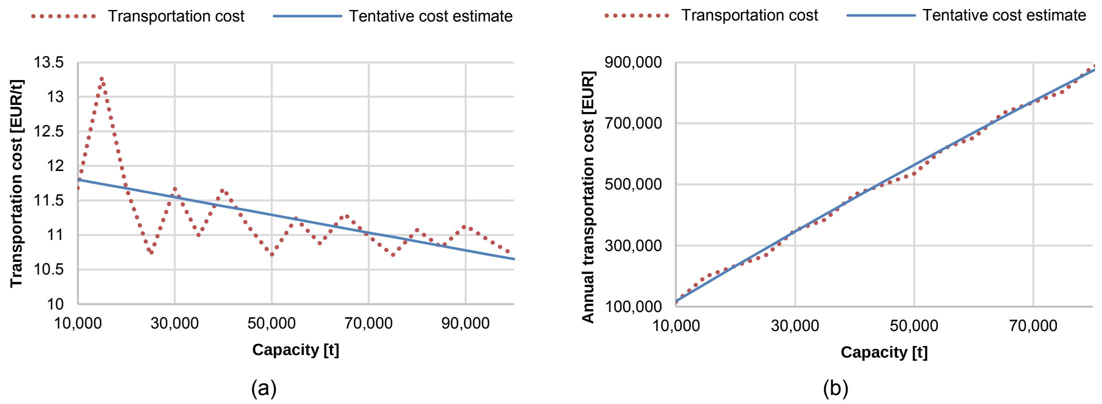


Figure 5: (a) Quantification of waste transportation costs for various annual capacities, (b) Quantification of annual waste transportation costs for various annual capacities and 90 kt/y distance

Amount of transported waste along the edge is still unknown, the whole transportation cost are defined by Eq(1):

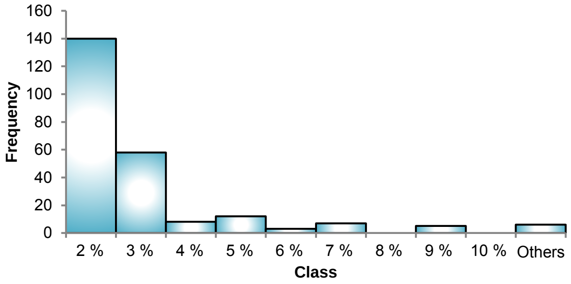
$$Transportation\ cost = Capacity \cdot Cost_{Transport\ per\ ton}(\text{Capacity}) \tag{1}$$

where unit price for transportation depends on the amount of transported waste (Figure 5(a)). Product of two unknown quantities in an objective function leads to a non-linear task. The non-linearity would seriously complicate the task. But the difficulty may be resolved by modifying Formula 1 where the variable is only in the form of transported waste amounts Eq(2) and Figure 5(a):

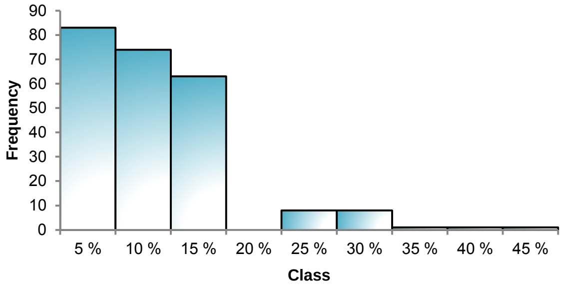
$$Cost_{Transport\ per\ ton} \cdot Capacity_{\ edge} \tag{2}$$

Unit price for transportation (Figure 5(b)) is then eliminated from the task completely, and only total costs remain. Dependence of total costs on amount of transported waste is pre-calculated from the unit price before the optimisation task. Non-linear dependence is approximated with a linear model (Figure 5(b)).

Degree of simplification introduced by linearisation was tested on a real transport network model. We picked one of the waste-to-energy facilities that was connected with other nodes. Each edge (total of hundreds of mini-edges) had a predefined length and their dependencies were computed as in Figure 5(a) and 5(b); the final dependence was approximated with a linear dependence. Figure 6(a) illustrates maximum deviations (that is differences between saw-like function and the linear model); Figure 6(b) illustrates average deviations of all considered distances.



(a)



(b)

Figure 6: (a) Histogram of model maximum deviation, (b) Histogram of average deviation for 10 – 100 kt/y interval

Most deviations in the linear model occur for transportation of small amounts of waste. This situation is further amplified for edges with short distance (ca. max 10 km). If the distance is longer, that is more than 10 km and max. ca. 240 km, the average deviations on one edge do not exceed 10 %. This is an acceptable deviation caused by simplification of the computations, and most of all a huge benefit for NERUDA applications. Techno-economic transportation models are a powerful tool for creating of transport prices.

4. Conclusion

This paper analyses one of the most important elements of complex transportation networks models, which is the transportation cost. Complex techno-economic models of various transportation systems were formulated and used within complex analysis. The major results are that in addition to the distance the unit cost significantly depends on the amount of waste. Comparison of variable (actual) transportation cost with linear (theoretical) transportation cost is the core of the paper. These two costs were compared and a deviation was identified. Detailed examination proves that major deviations occur in short distances (max. ca. 10 km). This further leads to a conclusion that a transport cycle, that is transport from A to B and back, is most sensitive on 20 – 30 km distances. Transportation cost may be fixed as a constant, with an acceptable deviation, for higher mileage. This is a huge plus for any network flow model incl. NERUDA as the cost may be fixed before the computation, and thus becomes an input.

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