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A MULTIMODAL FREIGHT COLLABORATIVE HUB LOCATION AND NETWORK DESIGN PROBLEM

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2012

A MULTIMODAL FREIGHT COLLABORATIVE HUB LOCATION AND NETWORK DESIGN PROBLEM

by

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THESIS

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This thesis is jointly supervised by the following faculty members:

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ABSTRACT

The study presents an analytical framework to explore the rail-road collaborative paradigm.

New collaborative technologies have been developed in recent years and they offer a potential solutions and opportunities for collaboration among all modes of transportation. The most progressive technologies that could fulfill the gap in rail-road collaborative paradigm are identified and presented in this research.

The research deals with current state and possible development of collaboration of rail and highway modes of transportation, referred to as rail-road collaboration. Multimodal transportation is the shipment of goods in a single transportation unit. The longest part of the route takes place by rail, inland waterway or sea without handling the goods themselves and for a collection or a final delivery highway mode of transportation is usually used.

The main factor for the creation of efficient multimodal transportation network is an appropriate location of multimodal facilities and effective routing through existing transportation network with focus on minimizing the operational costs. The review of developed mathematical models related to this issue is part of this research. The developed models help to determine the internal costs of intermodal collaboration on a freight transportation network. The internal costs consist of operational costs incurred by transportation and intermodal facility operators. These models were not considering time-dependent costs of goods tied in transit. A case study of developed models is applied to sample networks. The dependency of total cost performance on level of collaboration is discussed in sensitivity analysis.

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Chapter 1: INTRODUCTION

Freight transportation has undergone remarkable developments over the past decade as a result of synergy of these factors: economic development, infrastructure improvement, and technological innovation. Generally speaking, freight transportation follows the development of economic activity. Improving infrastructure and technological innovations make freight transportation more efficient and productive in matters of rates, transit times, safety and accuracy.

If one compares the different land freight transportation modes, it is evident that the highway sector dynamically grows while other sectors stagnate. There are several reasons: speed service from house to house and accuracy of road transportation, more favorable rates and flexibility of procedures, and lack of adequate and competitive actions by other modes of transportation, especially railroads.

This expansion of the highway transportation is not without consequences for the environment and society. External costs continued to grow, highway transportation becomes the biggest source of pollution, and highways are more and more congested.

Since the advent of the Internet in the 1990s, the rail and ground freight transportation industries have become more competitive than ever before. Shippers, usually larger manufacturers and retailers, have increased their transportation requirements due to innovative inventory practices and increased activity in e-commerce, and in turn have spurred competition (Song and Regan, 2004). In addition, the Internet, along with information communication technologies (ICT), is prompting changes to the structure of transportation marketplaces by fostering more spatially spread demand (Anderson et al., 2003). These innovations have created new challenges for rail and ground freight transportation in the form of increased costs related to deadheading (moving empty) and increased energy prices.

Furthermore, as the global economy continues to recover from the effects of the most recent recession, an increase in total freight movements is predicted for the European Union

(European Commission White Paper, 2011). With this projected growth coupled with roadways already at capacity, European countries will experience increased congestion. To mitigate the effects of congestion, the European transportation industry is exploring new and innovative paradigms that provide relief to an aging roadway infrastructure. One such paradigm is the concept of collaborative multimodal transportation systems. The concept of collaboration amongst transportation companies is not a new one (Figlozzi, 2003; Song and Regan, 2004; Bailey et al., 2011; Hernandez et al., 2011; Hernandez and Peeta 2011; Bailey, 2011), however, collaboration across transportation modes has received little attention. This is especially true for collaborative efforts with regards to the European Union. The challenge of such collaboration is in "how" and "what" will drive the collaborative efforts.

With this in mind, collaboration between rail and ground freight transportation has emerged as a deployable alternative to improve fleet usage, increase operational efficiency and energy usage. This research attempts to fill the gap in current collaborative transportation literature from the perspective of multimodal transportation systems. In addition, this research seeks to develop a multimodal collaborative models to gain insights on the viability of the collaborative paradigm with regards to multimodal transportation, and with special consideration to the European Union transportation system.

1.1 Objectives of the Thesis

The study seeks to develop new mathematical methodology to address best locations of intermodal facilities and multimodal routing through a network according to input cost parameters and existing road and railway networks. The proposed mathematical model should enable decision-makers to select the optimal number of facilities to locate, to choose the best placements of these facilities on the existing network, and to determine the best usage of network through network design modeling.

The basic objectives are:

1) Review the current stage of art of the collaborative rail-road transportation paradigm from following perspectives. First, to provide the development of rail-road collaboration. Second to mention the advantages and disadvantages of rail-road collaboration. Third, to identify the technologies of multimodal collaboration. Fourth, to provide the collaboration location models and fifth, to provide an overview of collaborative network design problem.
2) Identify all cost parameters that affect the total costs of entire multimodal chain that includes railway costs, road costs and the costs that occur during the change of transportation mode.
3) Development of model to address the freight multimodal facility location problem.
4) Development of model to address the freight multimodal network design problem.
5) Implement an experiment based on developed models.
6) Provide the sensitivity analysis of multimodal facility location model to derive insights for decision-makers. This is done by analyzing the model for different input parameters.

1.2 Organization of the Thesis

The remainder of the thesis is organized as follows. Chapter 1 introduces the topic of this paper and lists the goals of the thesis. Chapter 2 provides an overview of the relevant literature in the problematic of current state of rail-road collaboration with focus on advantages and disadvantages of multimodal collaboration. In this chapter are also presented the multimodal collaboration technologies and the main part provides the overview of multimodal collaborative location models and multimodal network designs. Chapter 3 provides the calculation of multimodal costs. Chapter 4 defines the mathematical model for multimodal freight facility location problem and following chapter 5 defines the mathematical model of multimodal freight network design problem. Next chapter 6 includes a theoretical application of usage of developed

models. In the last chapter 7 are summarized the benefits of the thesis, its contributions, and the possible future research work on the thesis issue is provided.

Chapter 2: LITERATURE REVIEW

This chapter provides a review of previous research that is relevant to the problem addressed in this study. This section is organized as follows: The current state of rail-road collaboration is discussed in section 2.1; Section 2.2 discusses the advantages and disadvantages of multimodal collaboration. Section 2.3 introduces an overview of multimodal collaboration technologies. Section 2.4 discusses the multimodal facility location models followed by Section 2.5 which describes multimodal network design models. Section 2.6 presents some concluding remarks.

2.1 Rail-Road Collaboration in U.S. and Europe

While the collaborative concept is relatively new within the transportation domain, logistic networks can apply it in various forms. Most studies have primarily focused on road based transportation collaboration (Figlozzi, 2003; Song and Regan, 2004; Hernandez et al., 2011; Hernandez and Peeta 2011; Bailey et al., 2011; Bailey, 2011). However, studies examining the rail-road collaborative paradigm have been sparse, yet interest is increasing (Macharis & Bontekoning, 2004).

In a recent study by Kuo et al. (2008), the authors investigated collaborative decision-making (CDM) strategies that are proposed for the collaborative operation of international rail-based intermodal freight services by multiple carriers. The benefits of the proposed techniques are assessed using a carrier collaboration simulation—assignment framework on a real-world European intermodal network spanning 11 countries. Three CDM strategies are presented in this work: (a) train slot cooperation, (b) train space leasing, and (c) train slot swapping. The results of numerical experiments show that these strategies increased significantly in terms of shipments that are attracted to the proposed services. The best-performing CDM strategy, train slot

swapping, resulted in a more than 40% increase in terms of ton-kilometers attracted to proposed services.

From a U.S. perspective, the development of intermodal collaboration dates back to the end of World War II, when the American army started to use universal cargo units (container). This type of rail-road collaboration was the only one that was operated until the fifties. Most recently, custom road trailers appeared on rail wagons in the U.S. in response to increasing competition from road transportation which forced rail companies to collaborate with road transport operators. These trailers facilitate the possibility of collaboration through a more rugged trailer design and the railway gauge profile that allows the trailers to be transported via rail without reducing the height of rail cars (K-report, 2005).

In contrast, the European transport situation differs in that transport infrastructure that facilitates collaboration amongst rail-road transport is fairly new. That is, rail transport in Europe has experienced most of its advancements in recent years compared to the U.S. rail system. For example, multimodal systems in form of accompanied transportation referred to as RO-LA system (the name comes from the German name "Rollende – Landstrasse) have emerged. RO-LA is a mode of transportation where road vehicles are transported by another mode of transportation and are accompanied by their crew. Though RO-LA is a great idea and may facilitate collaboration, still there exist more disadvantages than advantages, for example:

- a high proportion of dead weight
- unused time of driving vehicles, and
- unused time of the crew of driving vehicles

These disadvantages may increase costs for a rail-road collaboration, however the prospective costs can be negotiated amongst a collaborative.

2.1.1 Rail and Road Freight Transport System Characteristics

The following subsections describe some characteristics of rail and road freight transport that are important in understanding the potential of the rail-road collaborative paradigm.

2.1.1.1 Direct Line and Line Haul Systems

A direct line system consists of line trains, which run in a session at a fixed time cycle for 24 hours and can pick or drop off transportation units in all locations. In this system, the transportation unit is transported across the shipping route in one railway carriages and transshipment takes place at terminals (most often direct shipments from origin to destination), from a truck to rail car and railroad to truck. The line system of direct trains is the simplest type of rail transport, and if traffic flows allows, even the most powerful and effective. Similarly, in truck-based freight transport line haul operations consist of direct routes between terminals, origin-destination pairs etc.

These systems have the advantage of moving goods directed between terminals. With regards to road-based transport the line haul provides opportunities for collaboration by originating at rail terminals and moving goods directing to final destinations (e.g., retailers etc.). However, these systems in isolation do not provide advantages for a rail-road collaborative but when a there are many over a large connected network the possibilities are greater.

2.1.1.2 Network System

A network based system can be characterized as a network of transfer terminals operating in a freight transportation network. This system can be viewed as a collection of direct line and line haul transport systems as earlier mentioned. Under a collaborative context, the network system can be presented as a multimodal transportation system that can behave as a hub-and-spoke or point-to-point system. The advantages of such a system is that it provides larger

coverage, increased number of potential collaborative transfer facilities, and increased number of collaborative routes.

2.1.2 Advantages and Disadvantages of rail-road Collaboration

The most important motivation for road transportation operators, which leads to the utilization of rail-road collaboration as an alternative to direct shipments by road or rail, is the fact that the offered transportation quality must be sufficiently comparable to the carriage by road or rail alone, for example at lower costs. The potential advantages of a rail-road collaborative are:

- An ecological transportation alternative,
- lower transportation costs,
- ensure the accuracy and regularity of delivery by avoiding unpredictable situations on the road (congestion, accidents ...),
- short-term storage of goods in handling units, thereby saving of costs associated with cargo space,
- the possibility of merging traffic flows, better utilization of vehicles,
- adapt to the trend in the future (Rondinelli and Berry, 2000; Bontekoning and Priemus, 2004; Caris and Janssens, 2008).

The potential disadvantages are:

- the need for initial non-recurring costs (road transportation - semi-trailer, operators - construction of terminals and reloading mechanisms),
- the possibility of transshipment only in terminals,
- consistent organization and planning of logistics activities,
- adaptation to the schedule and delivery dates of the trains (Rondinelli and Berry, 2000; Bontekoning and Priemus, 2004; Caris and Janssens, 2008).

Freight transportation is becoming a major challenge for road operators, because of the increasing customer demand on price, speed and reliability. Additionally, ground transportation operators are also coming under pressure due to increasing operating costs, especially labor costs, fuels prices, tolling and congestion costs. With this in mind, rail-road collaboration can provide increased efficiency in the transport of goods potentially decreasing costs and increasing capacity utilization. For rail-road collaboration to be effective the necessary infrastructure needs to be in place along with the technologies to facilitate the collaboration.

2.2 Loading Technologies That Support Rail-Road Collaboration

There are various technologies that facilitate rail-road collaboration transport. The first, is loading in a vertical manner loaded trailers (current method), using collets, cranes and various loading mechanisms. Second, loading horizontally (horizontal transshipment). This approach introduces new challenges, but the advantages of loading horizontally out weight those challenges. By loading horizontally, carriers have the option to either load the trailer or trailer and truck together. This provides greater flexibility especially in increasing collaborative participation in addition to reduced fossil fuel consumption by truck-trailer combinations. The following subsections describe in greater detail the current operational state and then the more recent horizontal loading methods.

2.2.1 Loading Vertically for Transshipment

The following subsections describe the vertically loading methods currently used by rail firms.

2.2.1.1 Piggyback System

The piggyback system is a vertical transshipment mechanism that uses lifts as shown in Figure 2.1. The basic elements of the piggyback are:

- cranes (gantry crane mechanisms),
- mobile reloading mechanisms (reloading mechanisms of road character)
- road vehicles (compilers and loaders, e.g. Mobiler).

Piggyback semi-trailers need to have a reinforced construction that allows for handling of the trailer and loading on the wagon in vertical movement (Lee et al., 2009).

Figure 2.1: Piggyback technology [http://www.viacombi.eu/fr/wp-content/uploads/2010/09/wagon-poche_1.jpg, Accessed February 2012]

2.2.1.2 ISU System

Innovativer Sattelanhänger Umschlag (ISU) system is an innovative way to move and load different types road-based trailers onto rail wagons. The ISU system largely depends on mobile crane systems that can load the trailer in a vertical faship It means that this system represents a vertical type of transshipment (Figure 2.2). The advantage is, however, use of standard pocket wagons. Companies using this system are currently ÖBB (Össterreichische Bundes Bahn), Rail Cargo Austria and Ökombi (Ökombi, 2012).

Figure 2.2: ISU technology
[http://www.handelszeitung.ch/sites/handelszeitung.ch/files/imagecache/content-leadimage/lead_image/26003490_732eeeeba2.jpg, Accessed February 2012]

2.2.2 Loading Horizontal for Transshipment

Compared to loading trailers vertically, loading horizontally reduces the overall costs of transshipments. The reasons are related to the following:

- Loading horizontally does not require special lifts and other lifting equipment, therefore cutting down on costs
- Trailers and truck-trailer combinations can easily board rail cars by simply rolling them into place, increasing safety to the cargo handlers.

The following subsections illustrate some the more recent and future examples of horizontal loading for transshipments.

2.2.2.1 Bimodal System

This system was originally developed in USA and allows the chassis of a trailer to be used as a wagon for the train (Figure 2.3). The conversion is achieved through a bogie connection between each chassis. (Lee et al., 2009; Woxenius and Lumsden, 1994).

Figure 2.3: Bimodal technology [http://www.wig-wag-trains.com/DI%20Pages/DI%20Pics/Roadrailers/180311_Triple-Crown-Micro-Logo.JPG, Accessed February 2012]

2.2.2.2 Modalohr System

Originating in France, the Modalohr system serves as a transportation vehicle and as a part of a station (Figure 2.4). The Modalohr is simply a rotary loading bridge on wagons which rises from its anchor embedded in the track using rollers that are powered by a hydraulic drive motor. In essence, creating a saddle bridge taxi, which provides a platform for the loading and unloading of the trailers. If the rail platforms are equipped with many Modalohrs, multiple truck-trailer loadings and unloading can take place (Lee et al., 2009; Modalohr, 2012).

Figure 2.4: Modalohr technology [http://www.modalohr.com/images/modalohr_operation2.jpg, Accessed February 2012]

2.2.2.3 CargoSpeed System

This technology is another variation of principle Modalohr and is still in development (Figure 2.5). This loading mechanism utilizes above grade ramps allowing for truck and truck-trailers to manure into place (Lee et al., 2009; CargoSpeed, 2012).

Figure 2.5: CargoSpeed technology [http://cargospeed.net/images/components/twist.jpg, Accessed February 2012]

2.2.2.4 Flexiwaggon system

The flexiwaggon system is a Swedish trailer loading system which is relatively new and still under development (Figure 2.6). The wagon is modified for simple horizontal loading and unloading of trailers, road vehicles, and container vehicles. In addition, only truck drive is needed to perform the transshipment. The great advantage of this system is load capacity of the loading vehicle, which can resist up to 50 tons (Lee et al., 2009; Flexiwaggon, 2012).

Figure 2.6: Flexiwaggon technology [http://www.ecoprofile.se/db/images/post11445.jpg, Accessed February 2012]

2.2.2.5 Cargoroo System

In 1999, the company Deutschland GmbH Adtranz developed an automatic loading system (ALS) known as CargoRoo Trailer (Figure 2.7). The CargoRoo works through two tracked rovers that are part of the wagon car, which guide the trailer onto the rail wagon (Lee et al., 2009; Stellmacher, R., 2001).

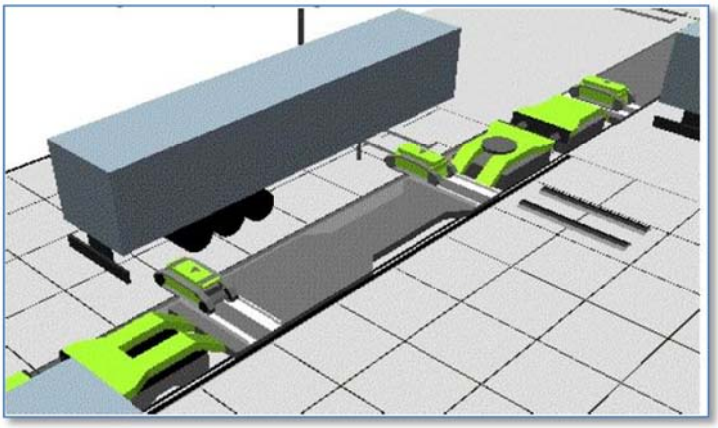

Figure 2.7: Cargoroo technology [http://www.zukunft-mobilitaet.net/wpcontent/uploads/2010/09/cargoroo_adtranz_waggon_auflieger.jpg, Accessed February 2012]

2.2.2.6 Cargobeamer System

Finally, Cargobeamer is an automated horizontal sliding system (Figure 2.8). This system allows existing transportation units, such as road semi-trailers, swap bodies and containers to be loaded with relative ease. The Cargobeamer can load up 32 trailers in about 10 minutes, this is because the loading and unloading takes place simultaneously (since the setup of the system runs parallel to the actual rail track system (Lee et al., 2009; CargoBeamer, 2012).

Figure 2.8: Cargobeamer technology [http://www.nw-news.de/_em_daten/_dpa/2010/11/29/101129_1813_cargobeamer1.jpg, Accessed February 2012]

In summary, the available technologies that facilitate rail-road collaboration can make the transshipment of truck based trailers possible. The transshipment can either take place in a vertical loading fashion (would require special equipment and additional resources to ensure safety) or horizontally (reduces the special equipment needed as well the manpower need for the loading and unloading of the trailers).

2.3 Collaborative Multimodal Facility Location Models

The key elements in multimodal collaboration models are so-called hubs (e.g., intermodal facilities). Hubs are special nodes in which there are two or more transportation networks (in this study we focus on the rail and road networks) of different modes connected and that a change or transfer of modes is possible. These hubs are usually associated with large amounts of concentrated flows and allow for the transfer and consolidation of shipments. These types of

hubs provide an economic benefit and environmentally friendlier alternative to road based modes of transportation.

Arnold et al. (2004) studied the optimal location of intermodal freight terminals in the Iberian Peninsula to demonstrate the impact of changes in transportation modal shares and their implications to the spatial flows across Europe. In their paper a heuristic method was used namely the ITLSS (Intermodal Terminals Location Simulation System) which is based on a particular representation of the transportation system that explicitly uses the concept of multimodality. The advantage of this method is that it allows for multiple-scenario testing (e.g., testing supply / demand variations, alternative objective functions, etc.). The work specifically considered five scenarios. It turns out that the share of transportation of goods, which have their origin or destination in Iberia is very sensitive to changes in relative costs of rail. The location of new terminals will not raise any significant share of combined transportation and relocation of existing terminals in Spain and Portugal (up to the minimization of transport costs) also has little or no effect. An issue with the proposed methodology is that it may not be transferable to other rail systems due to differences in the rail infrastructure. That is, rail companies originating in Spain for example would not be able to traverse the rest of Europe because of differences in their rail gauge. However, a collaborative between rail companies could be established to create intermodal facilities that would facilitate the transfer of the cargo in cross-border operations.

Limbourg and Jourquin (2009) try to find a solution that would lead to the fulfillment of one of the objectives of the European Common Transport Policy that is to restore the balance between modes of transportation and the intermodality. To promote this, the commission has launched the Marco Polo Programme, the objective of which is it to transfer 12 trillion ton-km/year transfer from road to ton-km/year other modes of transportation in Phase 1, rising 20.5 bn ton-km/year it in Phase II. The model used in this paper was a p-hub location problem. Their methodology and computer implementation offer optimization tools that can be used by policy makers in the international hub-and-spoke rail network. They work found that the location of the

current seven European centers create optimal hub-and-spoke network. Performance with optimal configuration, which results from the model (the same number of nodes), is more than three times better in terms of reducing ton.km / year for road transportation. This solution would reach 35% of Marco Polo I annual targets.

Taniguchi et al., (1999) introduced the concept of public logistics terminals (multi-company distribution centers) to Japan to help alleviate traffic congestion, environment, energy and labor costs. They described a mathematical model for determining the optimal size and location of logistics terminals that explicitly takes into account the conditions on the road network. The model incorporates queuing theory and nonlinear programming techniques and assumes user equilibrium with variable demand for the assignment of pickup/delivery trucks in urban areas. The model was applied to an actual road network in the Kyoto-Osaka area. A Genetic algorithm solution approach was found to be effective in obtaining optimal solutions for logistic terminals. The optimal location of logistics terminals were generally at junctions of expressways and close to large cities, because of the heavy congestion on many ordinary roads which generates an increase in transportation costs. The drawback of this work is that the authors did not consider the use of railway network. If the model used the combination of rail and road transportation networks, it would be possible to reach more efficient logistics systems through cost reductions along with less environmental impact and energy savings.

As in the problem addressed here, Nozick, and Turnquist (2001) also look at designing an efficient logistics systems through the identification of locations for distribution centers (DCs). In the paper the optimization of these location decisions requires careful attention to the trade-offs among various costs as such facility, inventory, transportation, and customer responsiveness. The location model presented was based on cost minimization and on a mathematical model to maximize coverage to ensure that a proportion of demand is within a specified "coverage" distance of a DC (Church and Re-Velle, 1974; Hillsman, 1984). This formulation facilitates the integration of coverage maximization and cost minimization. The application of above model

was illustrated the model was applied to an automotive manufacturer serving the continental US through discrete demand areas.

A recent study by Jeong at al. (2007) introduces a hub-and-spoke network problem for railroad freight, where a central planner is to find transport routes, frequency of service, length of trains to be used, and transportation volume. With the rise in membership in the European Community, it is logical to expect greater flows of trans-border freight when a bigger challenge is to maximize the use of extensive rail networks exist in Europe. The authors formulated a linear 0-1 programming model and developed two heuristic algorithms to solve realistically-sized instances. This model was employed to identify potential locations for hubs.

Similar to our work, Sirikijpanichkul and Ferreira (2005) proposes that the location of terminals that is one of the most important success factors in intermodal freight transportation. The model developed in their paper takes into consideration the advantages and disadvantages of various multi-objective optimization techniques, in both classical and heuristic approaches, are evaluated and compared, the most appropriate model was selected to develop the terminal location evaluation model. The model was made up of four supporting modules including land use allocation and transport networks, financial viability, terminal user costs and environmental and traffic impacts. The authors also developed a new evaluation tool for intermodal freight terminal locations, including externalities, stakeholders' perception and behavior, model appropriateness, and impacts of terminal expansion; interdependency of terminals; and freight policy.

Rizzoli at al. (2002) presented a simulation model of the flow of intermodal terminal units (ITUs) among and within inland intermodal terminals that are interconnected by rail corridors. The terminal operators prefer to explore whether new management methodologies can improve the terminal performance before investing in new equipment or enlarging the area of the terminals. The computer-based simulation in their paper can provide the decision-makers to create the strategies for development. In the developed model, the user of the simulation can

define the structure of the terminal and the train and truck arrival scenarios. The simulator can be used to simulate both a single terminal and a rail network, that is, two or more interconnected terminals. The simulation user can also define the terminal structure and test alternative input scenarios to evaluate the impact of new technologies and infrastructures on existing terminals.

Racunica and Wynter (2005) present an optimization model developed to address the problem of increasing the share of rail in intermodal transport through the use of hub-and-spoke type networks for freight rail. The main objective of their paper is to achieve effectively and with minimal cost to social and environmental involve extensive use of combined transportation by the latest scenarios under study for the integration of freight transportation in Europe. In these scenarios for transportation in the EU is effort to use rail transportation, not only for the long haul and low cost distribution, as was the case until now, but over the medium-long distances as well. The model developed for this application is based on the incapacitated hub location problem. Furthermore, the model is able to accurately represent the economies of scale due to consolidation, accomplished through the explicit use of concave cost functions for inter-hub (and hub-to-destination) portions of each trip. The effectiveness of heuristics is such that the piecewise linear approximation does not lose, indeed the number of items considered for each curve may be large, and the problems which have 30 nodes are still easily solvable. The authors compared the empirical results from a much cruder, piecewise-linear approximations, which showed that the quality of this solution is indeed effected significantly by this simplification.

In summary, the current state of the art with regards to collaborative hub location by two or more modes is sparse. The majority of studies presented in this section were from the perspective of a single mode. However, in this study we focus in multimodal hub location models from the perspective of two models, namely, rail and road based transportation.

2.4 Multimodal network design problem

The problem of multimodal network design, which is most closely related to this study, was mentioned in the work of Crainic and Rousseau (1986). The authors divided the tactical planning of freight transportation into the following problems:

1) Service network design (routing) which is concerned with the type and level of service to be offered.
2) Traffic routing which determines how the traffic moves through the network (the routes through the service network, the terminals, the amount of freight using each route).
3) Terminal policies which determine the strategies for the consolidation of freight.

With focus on the second task, they examined the multimode, multicommodity freight transportation problem. They developed a model that solves the major problems within the scope of decision making for the design of a service network, the development of terminal policies and establishment of traffic routing through the service network.

In most studies related to our issue however, the emphasis is either on the freight transportation planning and operations (Crainic and Laporte, 1997), or through network design and transportation planning (Magnanti and Wong, 1984; Gendron et al., 1997), or the fixed charged network design (Costa, 2005; Magnanti and Mirchandani, 1990; Crainic, 2002; Melkote and Daskin, 2001).

Cranic and Laporte identify three different approaches of freight transportation planning. These three planning levels are strategic, tactical and operational. They differ in length of term where the strategic level represents a long term planning, tactical level represents medium term planning, and operational represents short term planning, respectively. This classification highlights how the data flows among the decision-making levels and how policy guidelines are managed and set. The authors discuss the service network design for intermodal transportation in

the form of intercity freight transportation. The modal split of various transportation modes is introduced with the possibility of collaboration.

Gendron et al. (1997) developed several formulations of network design problem; they are arc-based, path-based, and cut-based formulations. They divided the used methods into three categories simplex-based cutting plane algorithms, Lagrangean relaxation, and heuristics.

Costa (2005) presented a fixed-charge network design problem where, in order to use a link of network one must pay a fixed cost representing the cost of constructing a road, or installing an electric line, etc. One important area, related to our issue, is the service network design problem which arises in airline and trucking companies. The basic idea is to maximize the profit by setting routes and schedules given some resource constraints. This idea can be easily implement to the multimodal transportation where all resources are also limited and the total costs can be minimized.

Melkote and Daskin (2001) presented a model that optimizes facility locations and design of the underlying transportation. They identified that changing the network topology is often more cost-effective than adding facilities to improve service levels. The developed model has benefits over the classical simple plant location problem and its application was demonstrated using a small six-node network.

The less-than-truckload (LTL) aspect of freight transportation by truck is one of the problems which may be addressed by our method. Hernandez (2010) has recently made significant contributions to this field. Hernandez (2010) studies the problem of developing an econometric modeling approach to determine the propensity for carrier collaboration and developing an optimization model from static planning perspective but, also from a deterministic dynamic planning perspective for a single carrier of interest to gain insights on the potential for LTL carrier-carrier collaboration. The problems are formulated as a very large mixed logit model and a multivariate technique.

2.5 Summary

This chapter has summarized all relevant literature that could be found in relation to the proposed research. The overview of the literature indicates that the location and network design models are powerful tools that allow transportation operators to lower their costs, and effectively use the capacity of infrastructure and facilities. Overall, it was found that much of the literature focuses only on carrier-carrier collaboration and does not reflect the collaboration among various transportation modes, for example between rail and road-based transportation (rail-road collaboration). Our work aims to fill the gap between collaboration amongst different modes of transportation.

Many collaborative technologies were developed in recent years and they have a big potential to be implement and to become the next core transportation system.

The mathematical formulations developed in this work are the subject of the chapters that follow.

Chapter 3: MULTIMODAL COST PARAMETERS

Chapter 3 introduces the calculation of cost for a multimodal transportation. Section 3.1 introduces the problem multimodal costs calculation. Section 3.2 provides a mathematical representation of road costs as well as the notation for all parameters that occur through road transportation process. In Section 3.3 introduces the calculation method for rail costs. Section 3.4 discusses relevant calculations of transfer costs that come up when multimodal facilities are built and operated. The chapter concludes with a summary in Section 3.5.

3.1 Introduction

There are many issues that must be considered when addressing the freight multimodal network design and the multimodal facility location problem, especially from a collaborative context. The biggest factor is the transportation costs and their relation to the collaboration. In addition, when different modes are used in transportation chain, a transfer cost has to be included in total cost calculation. Transfer cost is the cost of transferring the cargo from one mode of transportation to another (Boardman, 1997). Figure 3.1 illustrates the generic cost structure of multimodal transportation. The following sections highlight the costs used and implemented for the rail-road collaborative paradigm.

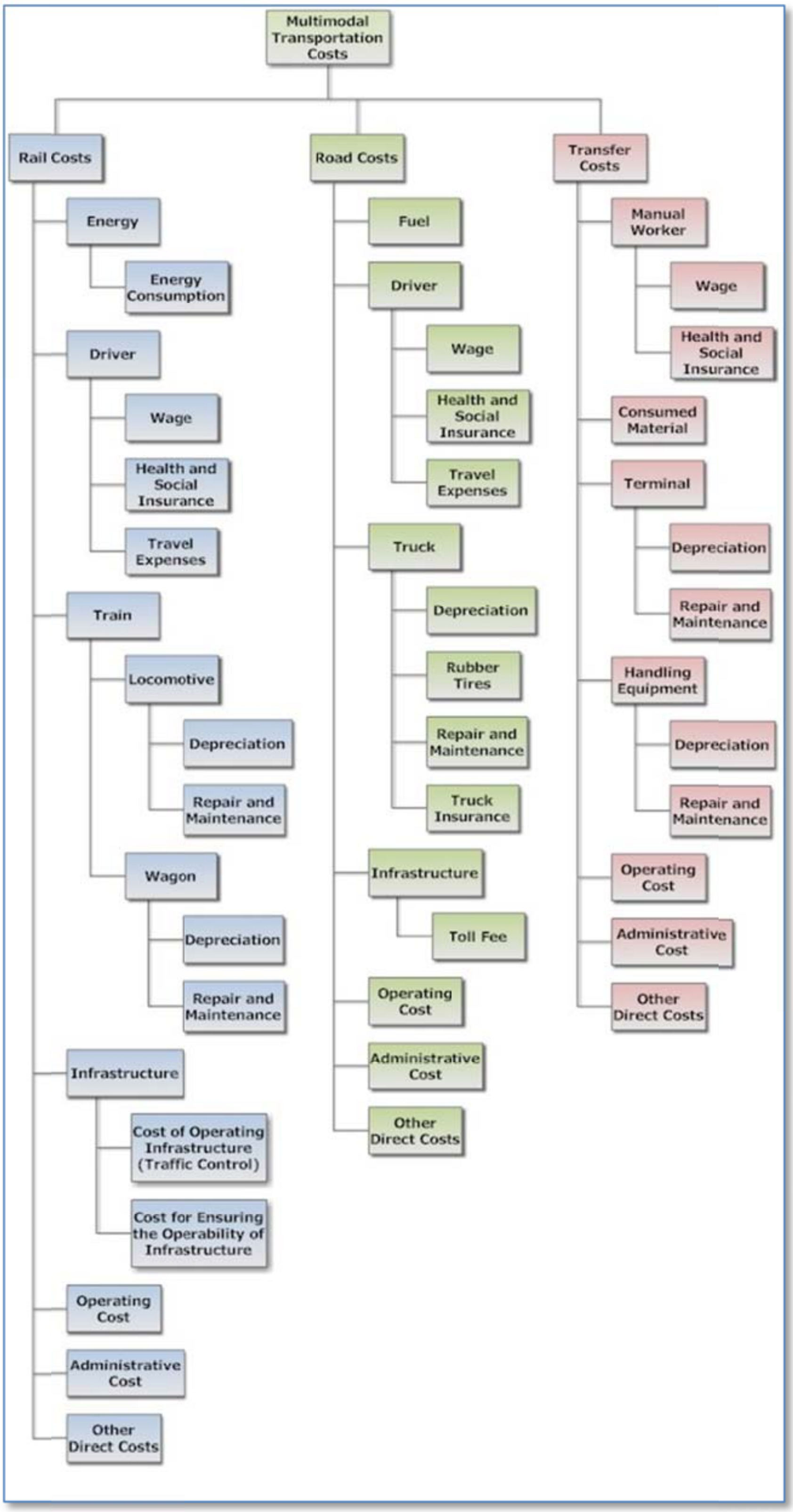

Figure 3.1: Multimodal Cost Structure

3.2 Rail Costs

The total costs of rail transportation can be divided into: Dependent (variable), these costs include the costs:

a) mileage (such as costs for the use of infrastructure),

b) hours of operation of the vehicle (such as energy consumption, wages, etc.).

Independent (fixed) costs are independent of volume of cargo (e.g. per km or hour). They are intended as an absolute value due to their content and structure. They occur throughout the operation of vehicle and must be added to additional at each calculation unit (which means miles traveled, or hours of operation of vehicle). These costs include depreciation, insurance, etc. The following table illustrates the cost breakdown for the rail costs followed by the notation and rail cost Ω equation.

Table 3.1: Rail Cost Division

Entry	**Cost Calculation**		
	Variable Costs		**Fixed Costs**
	km	**h**	
Energy Consumption		x	
Payroll		x	
Depreciation of Locomotive			x
Depreciation of Wagon			x
Repair and Maintenance of Locomotive			x
Repair and Maintenance of Wagon			x
Health and Social Insurance		x	
Travel Expenses		x	
Other Direct Costs			x
Operating Cost			x
Administrative Cost			x
Cost of operating infrastructure	x		
Cost for ensuring the operability of Infrastructure	x		
Total Cost	---	---	---

The following are the notation for the rail costs Ω where:

Ω	Collaborative cost rate [EUR/km]
α	Average energy price [EUR/kWh]
γ	Average energy consumption [EUR/1,000 gross ton km]
w_l	Average weight of a locomotive [ton]
w_w	Average weight of a wagon [ton]
w_t	Average weight of a trailer [ton]
w_c	Average cargo weight [ton]
δ	Cost per 1 train kilometer of operating infrastructure (traffic control) [EUR/km]
l_{max}	Average maximal length of train [m]
l_l	Length of a locomotive [m]
l_w	Length of a wagon [m]
ε	Cost per 1000 gross ton kilometers for ensuring the operability of Infrastructure [EUR/1000 gross ton km]
η	Average hourly wage of a train driver [EUR/h]
θ	Average multimodal train speed [km/h]
θ	Percentage of wage for health and social insurance [%]
л	Travel expenses [EUR/h]
κ_l	Average original cost of locomotive [EUR]
λ_l	Average lifetime of a locomotive [year]
ζ_l	Average operating mileage per locomotive per year [km/year]
κ_w	Average original cost of wagon [EUR]
λ_w	Average lifetime of a wagon [year]
ζ_w	Average operating mileage per wagon per year [km/year]
μ_l	Average cost of maintenance and repairs per locomotive per year [EUR/year]
μ_w	Average cost of maintenance and repairs per wagon per year [EUR/year]
ξ	Operating cost per year [EUR/year]
π	Administrative cost per year [EUR/year]
ρ	Other direct costs per year (insurance, material, etc.) [EUR/year]
τ	Government subsidies per wagon per kilometer [EUR/km]

The rail costs Ω can then be represented as:

$$\Omega = \left(\alpha \cdot \gamma \cdot \frac{w_l + \left(\frac{l_{max} - l_l}{l_w}\right) \cdot (w_w + w_t + w_c)}{1000} + \delta + \frac{w_l + \left(\frac{l_{max} - l_l}{l_w}\right) \cdot (w_w + w_t + w_c)}{1000} \cdot \varepsilon + \frac{\eta}{\theta} + \frac{\eta \cdot \frac{\iota}{100}}{\theta} + \frac{\text{л}}{\theta} + \frac{\kappa_l}{\lambda_l \cdot \zeta_l} + \frac{\kappa_w}{\lambda_w \cdot \zeta_w} \cdot \left(\frac{l_{max} - l_l}{l_w}\right) + \frac{\mu_l}{\zeta_l} + \frac{\mu_w}{\zeta_w} \cdot \left(\frac{l_{max} - l_l}{l_w}\right) + \frac{\xi}{\zeta_l} + \frac{\pi}{\zeta_l} + \frac{\rho}{\zeta_l} - \tau \right) \cdot \left(\frac{l_{max} - l_l}{l_w}\right)^{-1} \tag{3.1}$$

The following section introduces the road costs equation.

3.3 Road Costs

The total costs of road transportation can be divided into: Dependent (variable), these costs shall be apportioned to the costs:

a) depending on mileage (such as costs for fuel, tires, etc.),
b) dependent on hours of operation of the vehicle (such as travel expenses, wages, etc.).

Independent (fixed) costs are independent of volume of cargo (e.g. per km or hour). They are intended as an absolute value, due to their content and structure. They occur throughout the operation of vehicle and must be added to additional at each calculation unit (which means miles traveled, or hours of operation of vehicle). These costs include road tax, depreciation, insurance, etc. As with the rail costs the following table illustrates the cost breakdown for the road costs followed by the notation and road cost Ψ equation.

Table 3.2: Road Cost Division

Entry	Cost Calculation		
	Variable Costs		Fixed Costs
	km	h	
Fuel Consumption	x		
Rubber Tires	x		
Payroll		x	
Depreciation			x
Repair and Maintenance			x
Health and Social Insurance		x	
Travel Expenses		x	
Other Direct Costs			x
Operating Cost			x
Administrative Cost			x
Toll Fee	x		
Total Cost	---	---	---

The following are the notation for the rail costs Ψ where:

Ψ Non-collaborative cost rate [EUR/km]

α Average fuel price [EUR/l]

β Consumption coefficient depending on cargo weight [ton^{-1}]

γ Average fuel consumption [l/100 km]

w_c Average cargo weight [ton]

δ Number of wheels in the truck

ε Average cost per of tire [EUR]

ρ Average tire lifetime [km]

η Average hourly wage of a driver [EUR/h]

θ Average truck speed [km/h]

ι	Percentage of wage for health and social insurance [%]
л	Travel expenses [EUR/h]
κ	Average original cost of truck [EUR]
λ	Average lifetime of a truck [year]
ζ	Average operating time per truck per year [hours/year]
μ	Average cost of maintenance and repairs per truck per year [EUR/year]
ν	Toll fee per kilometer [EUR/km]
ξ	Operating cost per year [EUR/year]
π	Administrative cost per year [EUR/year]
ρ	Other direct costs per year (insurance, material, etc.) [EUR/year]

The rail costs Ψ can then be represented as:

$$\Psi = \alpha \cdot \beta \cdot \frac{\gamma}{100} \cdot w_c + \frac{\delta \cdot \varepsilon}{\rho} + \frac{\eta}{\theta} + \frac{\eta \cdot \frac{\iota}{100}}{\theta} + \frac{\text{л}}{\theta} + \frac{\kappa}{\lambda \cdot \zeta \cdot \theta} + \frac{\mu}{\zeta \cdot \theta} + \nu + \frac{\xi}{\zeta \cdot \theta} + \frac{\pi}{\zeta \cdot \theta} + \frac{\rho}{\zeta \cdot \theta} \quad (3.2)$$

The following section introduces the transfer costs equation.

3.4 Transfer Costs

The transfer costs can be divided into fixed and variable. They may depend upon the transfer point at which they occur, as well as the incoming and outgoing modes at a transfer point. The fixed costs depend mainly on the original construction cost of a terminal. This may vary based on used technology of transshipment and handling equipment. Other fixed cost elements are the operational and administrative cost. Variable costs are expenses that change according to volume of service in a terminal, such as costs of manual workers, costs of consumed material and etc. The total transfer cost per one unit of cargo is directly dependent on variable costs and indirectly on fixed costs. The most important issue for minimizing the total price of

transfer per one unit is to reach the maximum capacity of a multimodal transfer facility. The following table illustrates the cost breakdown for the transfer costs followed by the notation and road cost Φ equation.

Table 3.3: Transfer Cost Division

Entry	**Cost Calculation**	
	Variable Costs unit clearance	**Fixed Costs**
Payroll	x	
Consumed Material	x	
Depreciation of Terminal Construction		x
Depreciation of Handling Equipment		x
Repair and Maintenance of a Terminal		x
Repair and Maintenance of a Handling Equipment		x
Health and Social Insurance	x	
Other Direct Costs		x
Operating Cost		x
Administrative Cost		x
Total Cost	---	---

The following are the notation for the rail costs Φ where:

Φ Transfer cost rate [EUR/unit]

η Average hourly wage of a manual worker [EUR/h]

θ Number of loaded/unloaded units per hour [unit/h]

ι Percentage of wage for health and social insurance [%]

л Materials consumed during loading/unloading a unit [EUR/unit]

κ Construction cost of a terminal [EUR]

λ Average lifetime of a terminal [year]

ζ Average number of loaded/unloaded units per year [unit/year]

μ Cost of handling equipment [EUR]

ν Average lifetime of handling equipment [year]

δ Average cost of maintenance and repairs of a terminal per year [EUR/year]

ε Average cost of maintenance and repairs of handling equipment per year [EUR/year]

ξ Operating cost per year [EUR/year]

π Administrative cost per year [EUR/year]

ρ Other direct costs per year (insurance, material, etc.) [EUR/year]

The rail costs Φ can then be represented as:

$$\Phi = \frac{\eta}{\theta} + \frac{\eta \cdot \frac{\iota}{100}}{\theta} + л + \frac{\kappa}{\lambda \cdot \zeta} + \frac{\mu}{\nu \cdot \zeta} + \frac{\delta}{\zeta} + \frac{\varepsilon}{\zeta} + \frac{\xi}{\zeta} + \frac{\pi}{\zeta} + \frac{\rho}{\zeta} \tag{3.3}$$

3.5 Summary

In summary, the cost calculations that were presented above provide a calculation structure in order to transform the costs of all activities for calculation of core business activities per one specific unit. These activities are transportation of trailers for road and rail operators and transshipment of a trailers for multimodal terminal operators. In the case of rail transportation, it is necessary to mention that the method of calculation radically differs in Europe and USA because of different structures of rail infrastructure ownership. The infrastructure is owned by rail companies in USA in contrast with Europe where the rail infrastructure is owned by states. Also among the European countries can be found differences in rail cost calculation caused by variation in charge policy.

The presented calculation models do not include the profit element. The main purpose of this chapter was to develop a model of core cost calculations for transportation and transfer operators. For the calculation of total price that should be charged to shipper the calculation

should include the profit element also the VAT element, respectively. Complete structure of price is showed on Figure 3.2.

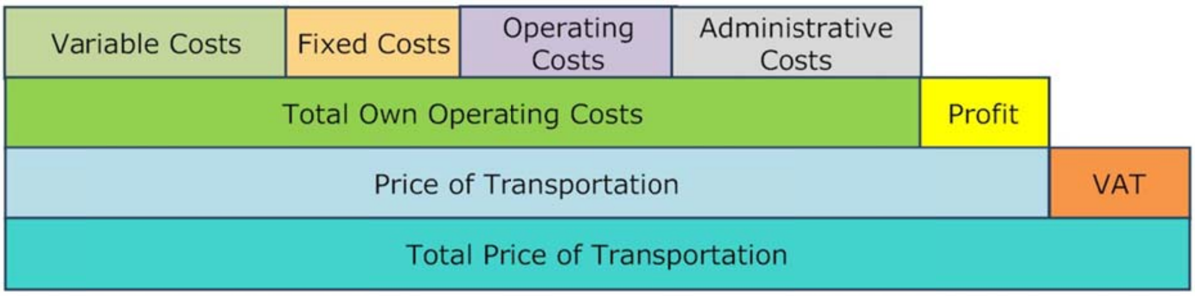

Figure 3.2: Total Price Structure

Chapter 4: A MULTIMODAL FREIGHT COLLABORATIVE HUB LOCATION PROBLEM

Chapter 4 introduces the formulation of the multimodal freight collaborative hub location problem addressed in the thesis. Section 4.1 introduces the problem. The mathematical model is developed in Section 4.2. This section presents the sets and indices, parameters, and defines the decision variables. This section also provides the set of constraints and defines the objective function. Section 4.3 provides some concluding comments for Chapter 4.

4.1 Introduction

When one is selecting a location for the multimodal facilities, it is necessary to proceed systematically, as it is a crucial decision, i.e. later unchangeable. The most important factor that influences the choice of a location for the establishment of a multimodal terminal is the existing transportation infrastructure network. Logistics centers cannot function effectively without efficient connections to a network of good quality and transportation infrastructure. In the case of a multimodal collaborative effort, such as rail-road collaboration, the need for facilities that can accommodate and facilitate collaboration is of great importance. So the problem becomes one of establishing (i.e., identifying) collaborative facilities that can support a rail-road collaborative. The following sections are our attempts to formulate the multimodal freight collaborative hub location problem (MFCHLP).

4.2 Mathematical Model, Problem Description and Assumptions

The MFCHLP seeks to determine a set of multimodal consolidation collaborative consolidation transshipment hubs for a rail-road collaboration that minimizes the total collaborative costs for the set of collaborating carriers (both the rail and road-based freight

carriers). Hence, a carrier in this system is classified as either a collaborative carrier (shares the costs to set up multimodal hubs), or non-collaborative (decides to ship directly). The operational networks of the collaborating carriers can be completely identical geographically or overlap in some segments relative to other carriers in the collaborative.

The collaborative rate structure of the collaborative carriers is represented by revenue oriented behavior. If a collaborative opportunity cannot be identified with regards to the multimodal collaborative hubs, a non-collaborative option is considered. It is assumed that the costs of shipping directly fall upon the carrier itself.

The following assumptions are made in the MFCHLP: (i) candidate multimodal collaborative consolidation hubs are uncapacitated, and (ii) heterogeneous products are shipped. In addition, the problem is deterministic in the sense that the demand is known and the available holding times at facilities are time invariant. By contrast, a stochastic version of the problem would entail stochasticity of demand of the collaborating carriers.

4.2.1 Indices and Sets

In MFCHLP formulation, a shipment from collaborative carrier $q \in Q$ enters the collaborative network through an origin facility $i \in I \subseteq \mathrm{N}$ and travel via multimodal consolidation candidate transshipment hubs $l, m \in N$ and exit through a destination facility $j \in J \subseteq \mathrm{N}$. Let d_{ijq} represent the number of trucks (or shipments) utilized by collaborative carrier $q \in Q$ from origin facility $i \in I \subseteq \mathrm{N}$ to destination facility $j \in J \subseteq \mathrm{N}$.

4.2.2 Parameters

Let Ω_{ijlm} be the collaborative carrier $q \in Q$ revenue oriented cost associated to a unit of demand d_{ijq} to travel between origin facility $i \in I$ to destination facility $j \in J$ when going via multimodal consolidation candidate transshipment facilities at node $l \in N$ and $m \in N$.

In addition, Φ_{lq} denotes the cost for collaborative carrier $q \in Q$ to establish a facility at node $l \in N$. Note that a collaborative carrier may choose to ship directly d_{ijq} without participating in the multimodal collaborative network if the collaborative cost is not significantly lower than the direct shipping cost, Ψ_{ijq}. Furthermore, a facility is established only if that facility has the capability to provide capacity for collaborative transshipment to take place, and this capacity is represented by h_l, h_m .

The maximum number of hubs opened is given by the parameter p.

4.2.3 Decision Variables

The formulation has three sets of binary decision variables:

(i) Y_{ijlmq} takes the value 1 if shipment originating from $i \in I$ headed to destination $j \in J$ by collaborative carrier $q \in Q$ travel via multimodal consolidation candidate transshipment hubs $l \in N$ and $m \in N$ and 0 otherwise,

(ii) Z_{ijq} takes the value 1, if carrier q ships the demand d_{ijq} directly without participating in the collaboration and 0 otherwise,

(iii) X_l takes the value 1 if a multimodal consolidation candidate transshipment hub is located at node $l \in N$ and 0 otherwise.

4.2.4 Constraints

$$\sum_{l \in N} X_l \quad = p \qquad \forall l \in N \qquad (4.1)$$

$$\sum_{l \in N} \sum_{m \in N} Y_{ijlmq} \quad + Z_{ijq} \quad = 1 \qquad \forall i \in I, j \in J, q \in Q \qquad (4.2)$$

$$\sum_{m \in N} d_{ijq} Y_{ijlmq} \leq h_l, X_l \qquad \forall i \in I, j \in J, l \in N, q \in Q \qquad (4.3)$$

$$\sum_{l \in N} d_{ijq} Y_{ijlmq} \leq h_m X_m \qquad \forall i \in I, j \in J, m \in N, q \in Q \qquad (4.4)$$

$$\delta_{ijlm} Y_{ijlmq} \leq w_{ijq} (1 - Z_{ijq})(1 - \beta) \qquad \forall i \in I, j \in J, l \in N, m \in N, q \in Q \qquad (4.5)$$

$$X_l \in \{0,1\}, Y_{ijlmq} \in \{0,1\}, V_{ijq} \in \{0,1\} \qquad \forall l \in N \qquad (4.6)$$

Constraints (4.1), (4.2), (4.3), (4.4) ensure the consistency between facility location and collaborative routing , i.e., shipments are routed through hub l only if a facility is established there. Constraint (4.2) and (4.5) ensures that a shipper will not participate in collaboration unless it is significantly lower than the direct routing costs.

4.2.5 Objective Function

The objective function of the MFCHLP minimizes the sum of transportation and construction costs generated by facility location. The objective function is represented as:

$$Min \quad \sum_{i \in I} \sum_{j \in J} \sum_{l \in N} \sum_{m \in N} \sum_{q \in Q} \Omega_{ijlm} d_{ijq} Y_{ijlmq} + \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} \Psi_{ijq} d_{ijq} Z_{ijq} + \sum_{l \in N} \sum_{q \in Q} \Phi_{lq} X_l \qquad (4.7)$$

It consists of three parts. The firs term represents the total shipment costs of carrier collaborating in multimodal transportation, second term represents the non-collaborating case and the last term represents the costs of multimodal hub terminals located in the network. The overall collaborative costs are obtained as the summation of collaborative rate Ω_{ijlm}, the demand d_{ijq}, and Y_{ijlmq}(the decision on whether collaboration is costly more efficient than direct shipping). The overall non-collaborative costs are obtained as the summation of the non-collaborative rate Ψ_{ijq}, the demand d_{ijq}, and Z_{ijq} (the decision on whether the direct shipping is costly more efficient than collaborative shipping). The overall costs of establishing the transfer facility in network are obtained as the summation of cost of establishing the facility Φ_{lq}, and X_l (the decision on whether the establishing of facility is effective).

The MFCHLP is known to be NP-hard as it reduces to a *p*-median problem (see Daskin, 1995). Since, these are the first attempts of formulating the MFCHLP (which is static) we use an exact method to solve the problem, namely the branch-and-cut algorithm (see CPLEX). As mentioned earlier additional dimensions such as time-dependency will require more sophisticated solution approaches such as meta-heuristics (e.g., genetic algorithms, tabu search, etc.).

Figure 4.1 is an illustration of the decision process for the MFCHLP:

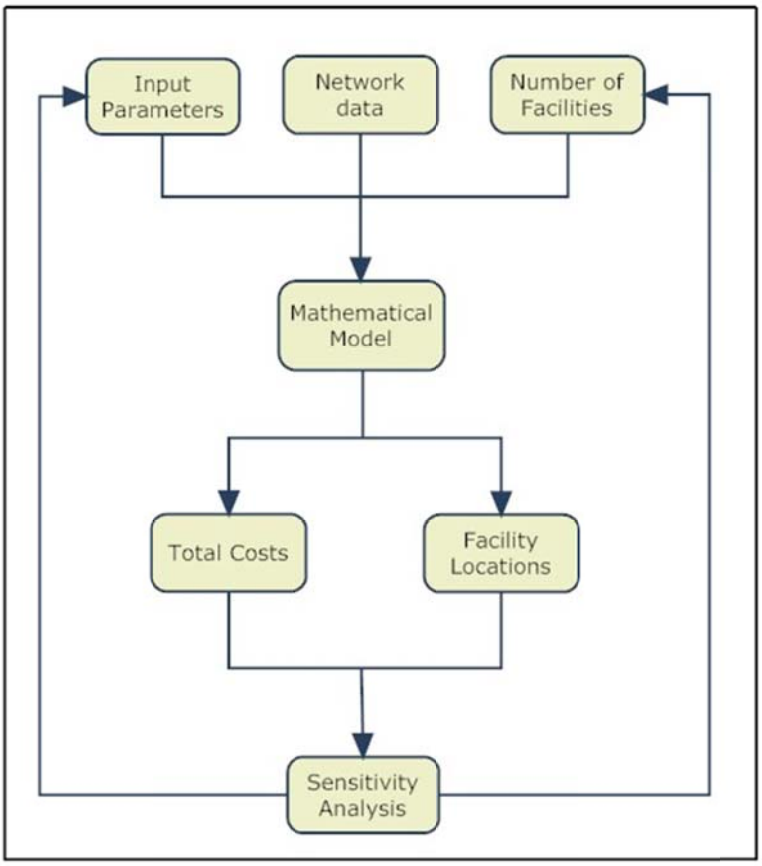

Figure 4.1: Location Model Schematic

4.3 Summary

The developed location model offers an optimization tool that can be used by decision-makers in the framework of a multimodal network. This tool can compute optimal locations of a determined number of hubs and show changes of adding additional hubs in the network. The schematic of proposed model is illustrated in Figure 4.1.

Chapter 5: A COLLABORATIVE FREIGHT MULTIMODAL FIXED CHARGED NETWORK DESIGN PROBLEM

Chapter 5 discusses the collaborative freight multimodal fixed charged network design problem addressed in the thesis. Section 5.1 describes the problem generally. Section 5.2 introduces the mathematical model, this includes formulation of sets and indices, calculation of input parameters and decision variables, finding of the limiting constraints, and formulation of objective function. Section 5.3 provides some concluding comment for this chapter.

5.1 Introduction

Fixed charged network design models are extensively used to present a wide range of planning and operation decision- making issues in transportation, telecommunications, logistics, and production. The basic approach of solving the collaborative freight multimodal fixed charged network design problem is from the point of view of the carrier. Compared to all previous models, the carrier here is offered an alternative route of rail transportation that might lower the total costs. This problem is called Static Multimodal Collaborative Carrier Problem (SMMCCP) and its formulation is presented in following chapter.

5.2 Mathematical Model, Problem Description and Assumptions

The SMMCCP seeks the appropriate network design from the predefined set of networks, to determine the routing for each O-D pair which minimizes the total transportation cost. Hence, the carrier of interest may use some free capacity from various multimodal train operators for the segments of route on which rail mode of transportation is available. Since this problem is static in the sense that the demand is constant and the available capacities from the collaborative

carriers are time invariant, a dynamic version of the SMMCCP would entail the availability of time-dependent collaborative capacities from the collaborative carriers and train operators.

The collaborative rate structure of the collaborative carriers is represented by revenue oriented behavior. If a collaborative opportunity cannot be identified with regards to the collaborative network design, a non-collaborative option is considered. It is assumed that the costs of shipping directly fall upon the carrier itself.

5.2.1 Indices and Sets

Let $G(N, A)$ denote an undirected network with node set N and link set A. The index i denotes a node in the network, $i \in N$ and $a \in A \subseteq N \times N$, where a denotes an undirected link that originates from the facility $i \in N$ is depicted as $a \in \Gamma(i)$ and this heading to facility $i \in N$ is $a \in \Gamma^{-1}(i)$ with nonnegative fixed costs. Let a shipment $k \in K$ be served by a transit corridor $a \in A$ through multimodal collaborative route served by carrier $m \in M$ and by multimodal train $q \in Q$ or through non-collaborative road served just by carrier $m \in M$. Fixed transshipment facilities $i \in N$, collaborative carriers $m \in M$ and multimodal trains $q \in Q$ form a collaborative network. A shipment $k \in K$ will enter the collaborative network through an origin facility $O(k)$ and exit through a destination facility $D(k)$. For each shipment $k \in K$ there is its origin-destination pair that origins in the facility $O(k)$ and directs to the destination facility $D(k)$.

5.2.2 Parameters

Each shipment $k \in K$ has an associated volume d_{mk}. The cost for acquiring a unit of capacity from collaborative multimodal transshipment via carrier $m \in M$ utilizing train $q \in Q$ on transit corridor $a \in A$ is a collaborative rate γ_{amq}. The fixed cost for transferring shipment to or from the train is included in the collaborative rate γ_{amq}. If the carrier does not use the collaborative transshipment, the non-collaborative rate is δ_{am}.

The available collaborative capacity of a multimodal train $q \in Q$ for transit corridor $a \in A$ is v_{aq}. If a multimodal collaboration of train $q \in Q$ is not provided for transit corridor $a \in A$, it is assumed without loss of generality that available collaborative capacity v_{aq} is 0.

5.2.3 Decision Variables

If shipment $k \in K$ takes place on transit corridor $a \in A$ to non-collaborative carrier $m \in M$, one defines y_{amk} to take the value of 1, and 0 otherwise. It represents the non-collaborative shipment transfer decision variable for the carrier of interest.

If a shipment $k \in K$ is served through transit corridor $a \in A$ by carrier $m \in M$ utilizing multimodal train $q \in Q$, one defines z_{amqk} to take the value of 1, and 0 otherwise. The variable represents the multimodal collaborative capacity for the carrier of interest.

5.2.4 Constraints

The formulation of constraints of SMMCCP consists of two sets of constraints. The first set of constraints (5.1; 5.2; and 5.3) model the independent transshipment of shipment through the collaborative route. The second set of constraints (5.4) establishes a limitation on the available collaborative capacity (or number of wagons) made available by train $q \in Q$ on transit corridor $a \in A$. The constraints are as followed:

$$-\sum_{m \in M} \sum_{a \in \Gamma(i)} \left(Y_{amk} + \sum_{q \in Q} Z_{amqk} \right) = -1 \qquad \forall i \in O(k), k \in K \quad (5.1)$$

$$\sum_{m \in M} \sum_{a \in \Gamma^{-1}(i)} \left(Y_{amk} + \sum_{q \in Q} Z_{amqk} \right) - \sum_{m \in M} \sum_{a \in \Gamma(i)} \left(Y_{amk} + \sum_{q \in Q} Z_{amqk} \right) = 0 \qquad \forall i \in N \backslash \{O(k), D(k)\}, k \in K \quad (5.2)$$

$$\sum_{m \in M} \sum_{a \in \Gamma^{-1}(i)} \left(Y_{amk} + \sum_{q \in Q} Z_{amqk} \right) = 1 \qquad \forall i \in D(k), k \in K \quad (5.3)$$

$$\sum_{m\in M}\sum_{k\in K} d_{mk} Z_{amqk} \leq v_{aq} \qquad \forall a \in A, q \in Q \quad (5.4)$$

$$\gamma_{amq}\, Z_{amqk} \leq \delta_{am}(1 - Y_{amk})(1-\beta) \qquad \forall a \in A, m \in M, q \in Q, k \in K \quad (5.5)$$

$$Y_{amk} \in \{0,1\} \qquad \forall a \in A, m \in M, k \in K \quad (5.6)$$

$$Z_{amq} \in \{0,1\} \qquad \forall a \in A, m \in M, q \in Q \quad (5.7)$$

Constraint set (5.1; 5.2; 5.3) represents the mass balance constraints and ensures the node flow propagation conservation for multimodal transportation shipment decisions; at most one decision unit of multimodal transport shipment is propagated at that facility. It consists of (5.1), (5.2), and (5.3), which correspond to the origin, intermediate, and destination nodes/facilities in the network, respectively.

Constraint (5.4) represents the train mode capacity constraint; it ensures that the capacity acquired from a carrier (left-hand side of (5.4)) is less than the available train mode capacity (right-hand side of (5.4)) on that transit corridor. Constrain (5.5) reflects the marginal effect through parameter β Constraint sets (5.6) and (5.7) represent the 0-1 integrality conditions for the decision variables.

5.2.5 Objective Function

The objective function of the SMMCCP seeks to minimize the total multimodal collaborative costs for multiple carriers and is represented as:

$$Min \sum_{a\in A}\sum_{m\in M}\sum_{k\in K} \delta_{am} d_{mk} Y_{amk} + \sum_{a\in A}\sum_{m\in M}\sum_{q\in Q}\sum_{k\in K} \gamma_{amq}\, d_{mk} Z_{amqk} \quad (5.8)$$

It consists of two parts. The first term represents the total shipment costs of carriers not collaborating, and the second term represents the multimodal collaborative transaction costs

between a carrier and rail company. The overall non-collaborative costs are obtained as the summation of non-collaborative cost δ_{am}, the demand d_{mk}, and the decision variable Y_{amk} on whether the direct shipping is more effective than collaboration. The overall collaborative costs are obtained as the summation of collaborative rate γ_{amq}, the demand d_{mk}, and the decision variable Z_{amqk}, that has value 1 if the collaborative route is costly efficient. In contrast of previous model, the fixed component of transfer cost is included in collaboration rate and the variable element as well.

The SMMCCP is known to be NP-hard as the problem size increases (see Ahuja et al., 1993; Hernandez and Peeta, 2010). Since, these are the first attempts of formulating the SMMCCP (which is static) we use an exact method to solve the problem, namely the branch-and-cut algorithm (see CPLEX). As mentioned earlier additional dimensions such as time-dependency will require more sophisticated solution approaches such as meta-heuristics (e.g., genetic algorithms, tabu search, etc.).

Figure 5.1 is an illustration of the decision process for the SMMCCP:

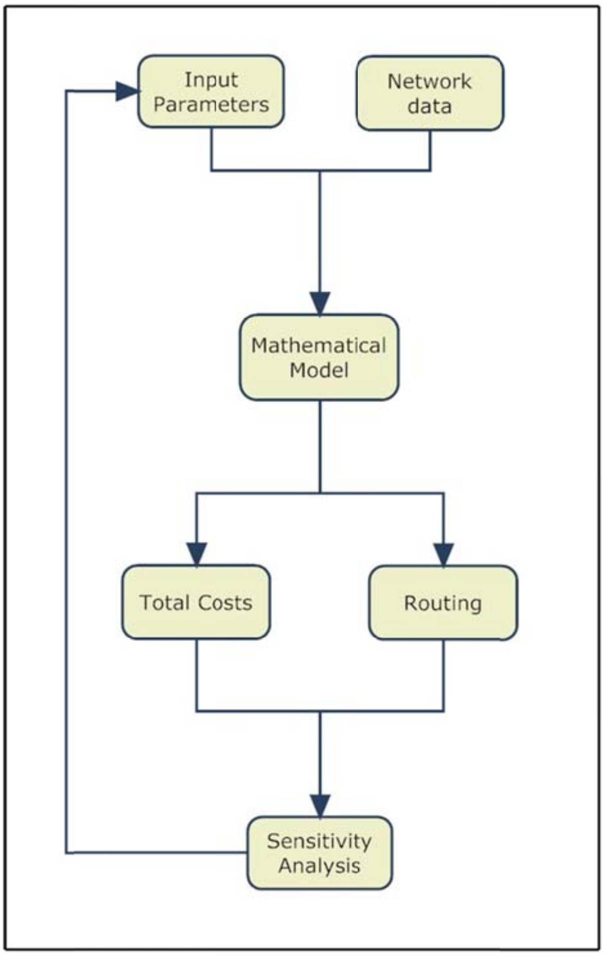

Figure 5.1: Network Design Model Schematic

5.3 Summary

The network design problem provides another perspective of optimization solution in transportation science. The developed routing model allows users to determine the optimal routing in a network system that achieves the minimization of costs. The only input parameters that enter the model are the cost input parameters and the network data. The presented model provides as its output the calculation of total costs generated by the system and the optimal routing (path) for transshipment of each commodity. The hub location model determines best location of facilities and network design model, based on specific locations of facilities, then enables to identify the best routing of collaborative shipments.

Chapter 6: APPLICATION OF MODELS

This chapter discusses computational experiments using test networks to seek insights on the performance of developed models as well as on the implications for practical applications. Section 6.1 discusses the data generation. Section 6.2 describes the 3 different size test networks. Section 6.3 discusses experiments and insights on model application using several test options. In Section 6.4 is provided the sensitivity analysis for key model parameters. The chapter concludes with a summary of the application insights.

6.1 Data Generation

The data needed for running the hub location experiment consist of cost matrices of collaborative routes, demand matrices, matrices that represent the cost to establish a facility as an intermodal collaborative facility, cost matrices of non-collaborative route, and matrices of rail capacities.

The network design model requires different set of input data. The set of rail capacities has to be defined. Another important modification can be found in demand. Demand is represented as a set of commodities that originate at a node *i* and destined to a node *j*. All demand data are formed in 3 matrices. The first one represents the value of commodity for each carrier; the other two matrices define the origin and destination nodes for each type of commodity. The network is defined in two separate matrices. The first one is the node-arc adjacency matrix and the second is the matrix in which is listed the set of arcs of the network.

The data generation of each input matrix is discussed below.

6.1.1 Non-collaborative route cost matrix

The non-collaborative cost matrix represents the cost of usage of road infrastructure. The costs matrices for each arc in the road network was created by multiplying the arc distance by the road cost parameter. The cost parameter varied between 0.95 and 1.05 was used to present the possible differentiation of costs for each route.

Also, the same data generation method for network design model was utilized. The only difference is that the road cost for each arc and each carrier were defined. In the previous model was used the same road cost for all carriers.

6.1.1.1 Road Cost Parameters

The calculation of road cost per kilometer is based on equation 3.2. This equation calculates the total road cost of transportation per 1 kilometer. The equation covers all costs that occur during the road transportation. All parameters are listed in Table 6.1. The input parameters in this experiment try to mimic the current conditions of road transportation in Czech Republic.

Table 6.1: Road Cost Input Parameters

Parameters	**Units**	**Monetary Value**
Fuel Consumption	l/100km	38
Fuel Price	Eur/l	1.45
Consumption Coefficient	ton^{-1}	0.04
Cargo weight	ton	25
Tire Cost	Eur/peace	245
Number of Tires	pieces	12
Tires Run Over	km	50,000
Wage	Eur/h	10
Price of the Truck	Eur	110,000
Lifetime of the Truck	years	6
Repair and Maintenance	Eur/year	0.15
Health and Social Insurance	% of salary	31
Travel Expenses	Eur/h	0.26
Truck Insurance	Eur/year	2300
Toll Fee	Eur/km	0.2
Operating Cost	Eur/year	1,900
Administrative Cost	Eur/year	1,600
Truck Operating Time	hours/year	2,200
Truck Speed	km/h	80

The diversification of cost components is listed in Table 6.2 and its graphical representation is illustrated on Figure 6.1.

Table 6.2: Road Cost Components Diversification

Entry	EUR/km
Fuel Consumption	0.551000000
Rubber Tires	0.049000000
Payroll	0.125000000
Depreciation	0.104166667
Repair and Maintenance	0.150000000
Health and Social Insurance	0.038750000
Travel Expenses	0.003250000
Other Direct Costs	0.013068182
Operating Cost	0.010795455
Administrative Cost	0.009090909
Toll Fee	0.200000000
Total Cost	**1.254121212**

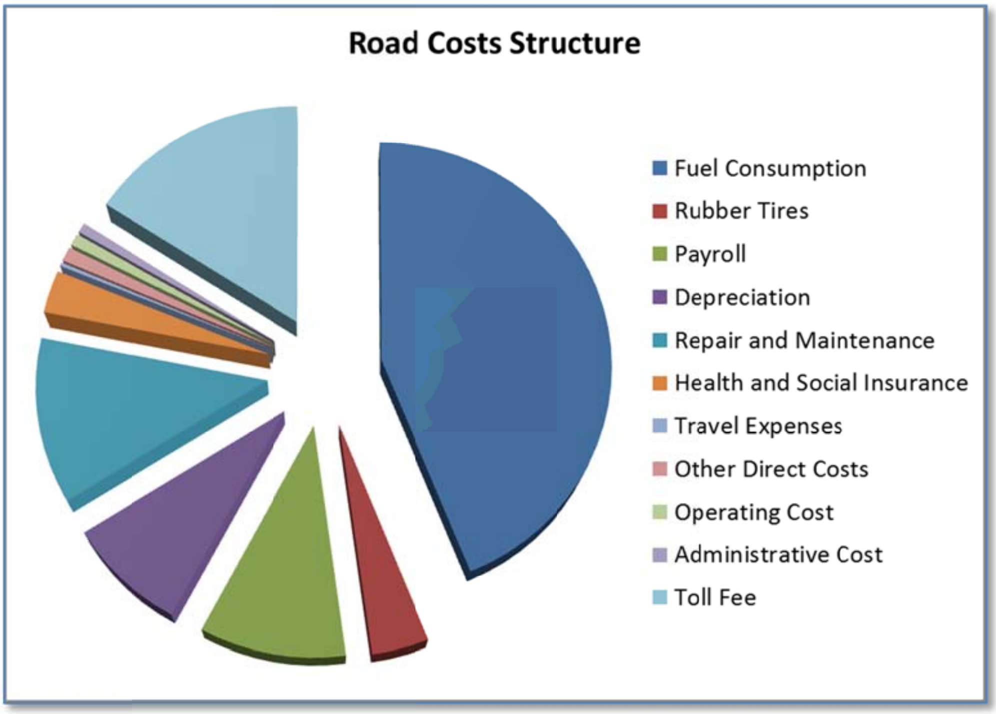

Figure 6.1: Road Costs Structure

6.1.2 Collaborative route cost matrix

This costs matrix represents the costs of transshipping of one freight unit from node i to node j through multimodal facilities l and m. The usage costs for each arc in the rail network were created by multiplying the arc distance by the rail cost parameter. The costs of the collaborative routes include also the variable component of transfer costs that occur during a transfer at a facility. The cost parameter varied between 0.95 and 1.05 to represent the possible differentiation of costs for each rail route.

The routing model requires slight modification, that is, the collaborative cost includes not just the variable component of transfer cost, but also the fixed cost that covers also the cost to establish the facilities. The structure of collaborative matrix was extended and involves the collaborative cost of each arc for combination of each carrier that can collaborate with a rail mode.

6.1.2.1 Rail Cost Parameters

The calculation of rail cost per one kilometer was more complicated than the calculation of the road-based costs. Big rail companies usually do not publish their internal information about cost calculations but, with cooperation of Czech national cargo operator (CD Cargo) it was possible to determine approximate cost parameters. They are listed in Table 6.3.

Table 6.3: Rail Cost Input Parameters

Parameters	Units	Monetary Value
Energy Consumption	kWh/1,000 gross ton km	20
Energy Price	Eur/kWh	0.18531
Weight of a Locomotive	ton	80
Weight of a Wagon	ton	20
Weight of a Trailer	ton	7
Cargo Weight	ton	25
Cost of Operating Infrastructure	Eur/km	0.98
Maximal Length of Train	m	700
Length of a Locomotive	m	20
Length of a Wagon	m	20
Cost for Ensuring the Operability of Infrastructure	Eur/1,000 gross ton km	1.30
Wage	Eur/h	14
Price of a Locomotive	Eur	3,250,000
Lifetime of a Locomotive	years	20
Price of a Wagon	Eur	280,000
Lifetime of a Wagon	years	18
Cost of Maintenance and Repairs of a Locomotive	Eur/year	50,000
Cost of Maintenance and Repairs of a Wagon	Eur/year	2,000
Health and Social Insurance	% of salary	31
Travel Expenses	Eur/h	0.26
Other Direct Costs	Eur/year	20,000
Operating Cost	Eur/year	50,000
Administrative Cost	Eur/year	15,000
Locomotive Operating Mileage	km/year	140,000
Wagon Operating Mileage	km/year	180,000
Train Speed	km/h	100

The individual components of calculation equation 3.1 are provided in Table 6.4. The cost structure is illustrated in Figure 6.2.

Table 6.4: Rail Cost Components Diversification

Entry	EUR/km
Energy Consumption	0.201442871
Payroll	0.004117647
Depreciation of Locomotive	0.034138655
Depreciation of Wagon	0.086419753
Repair and Maintenance of Locomotive	0.010869748
Repair and Maintenance of Wagon	0.011533333
Health and Social Insurance	0.001276471
Travel Expenses	0.000076471
Other Direct Costs	0.004201681
Operating Cost	0.010504202
Administrative Cost	0.003361345
Cost of operating infrastructure	0.028823529
Cost for ensuring the operability of Infrastructure	0.070658824
Total Cost	**0.46742452**

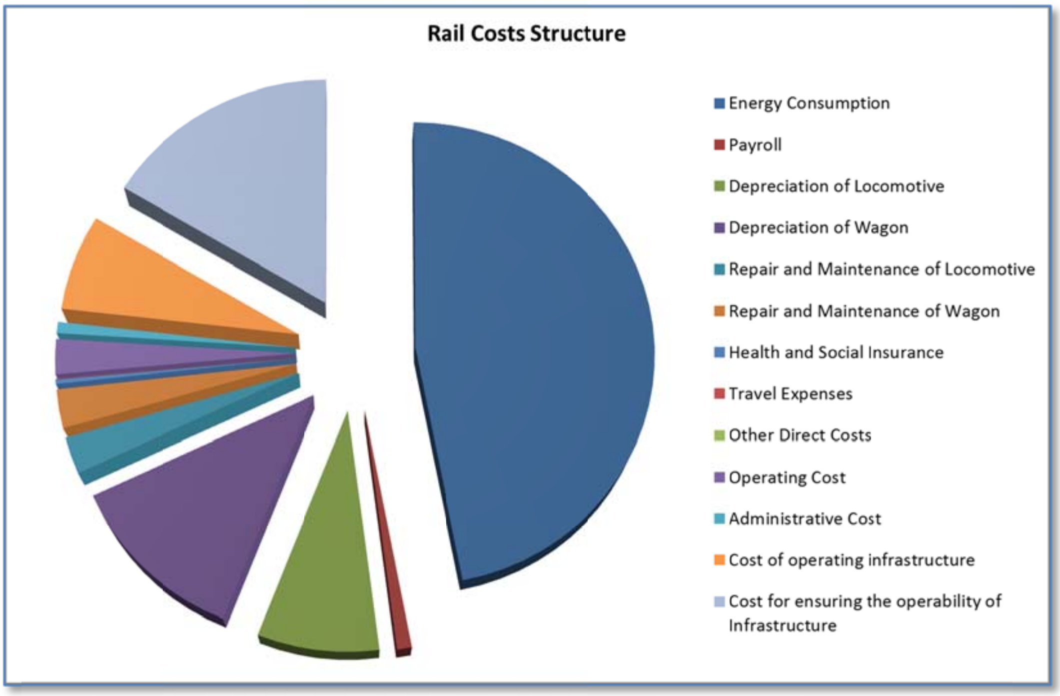

Figure 6.2: Rail Costs Structure

6.1.2.2 Transfer Cost Parameters

The calculation of transfer cost per one cargo unit covers equation 3.3. The parameters are based on estimation. It is not possible to get accurate parameters that could be based on realistic information, because the considered multimodal technologies are still under development. The Table 6.5 provides the estimation of parameters that occur in mathematical equation.

Table 6.5: Transfer Cost Input Parameters

Parameters	Units	Monetary Value
Wage	Eur/h	8
Loaded/unloaded units per hour	unit/hour	6
Health and Social Insurance	% of salary	31
Materials consumed during loading a unit	Eur/unit	0.5
Construction cost of terminal	Eur	4,000,000
Lifetime of the terminal	years	20
Average number of loaded/unloaded units per year	unit/year	20,000
Cost of handling equipment	Eur	250,000
Lifetime of the handling equipment	years	7
Cost of repair and maintenance of a terminal per year	Eur/year	90,000
Cost of repair and maintenance of handling equipment per year	Eur/year	10,000
Operating Cost	Eur/year	50,000
Administrative Cost	Eur/year	30,000
Other direct costs per year	Eur/year	60,000

Table 6.6 provides the diversification of cost components and the cost structure is shown on Figure 6.3.

Table 6.6: Transfer Cost Components Diversification

Entry	Fixed Costs	Variable Costs
	EUR/year	EUR/unit
Payroll		1.33
Consumed Material		0.50
Depreciation of Terminal Construction	200,000.00	
Depreciation of Handling Equipment	35,714.28	
Repair and Maintenance of a Terminal	90,000.00	
Repair and Maintenance of a Handling Equipment	10,000.00	
Health and Social Insurance		0.41
Other Direct Costs	60,000.00	
Operating Cost	50,000.00	
Administrative Cost	30,000.00	
Total Cost	**47,5714.28**	**2.24**
Total Cost per unit	**26.03**	

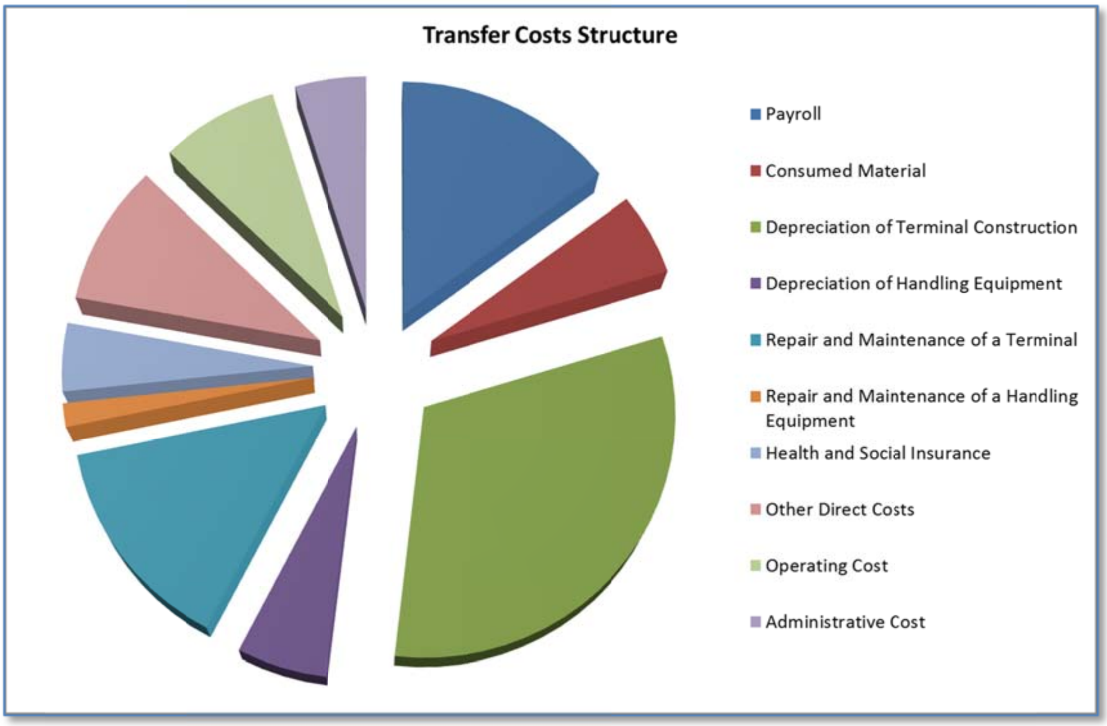

Figure 6.3: Transfer Costs Structure

6.1.3 The Test Networks

Three different size networks were created randomly. They are illustrated in Figures 6.4, 6.5 and 6.6. The networks consists of nodes that represent the origin and destination points, and arcs that represent the road (light blue lines) and rail (dark red lines) connections between nodes. The values represent the mileages between nodes in kilometers. The different complexity of calculations is demonstrated by use of different size of networks. The networks were randomly generated and all graphs are acyclic.

6.1.3.1 6-node Network

The smallest test network consists of 6 nodes and several connections between nodes. The total length of roads is 1,789 km and length of rails is 1,324 km. The network is illustrated on Figure 6.4.

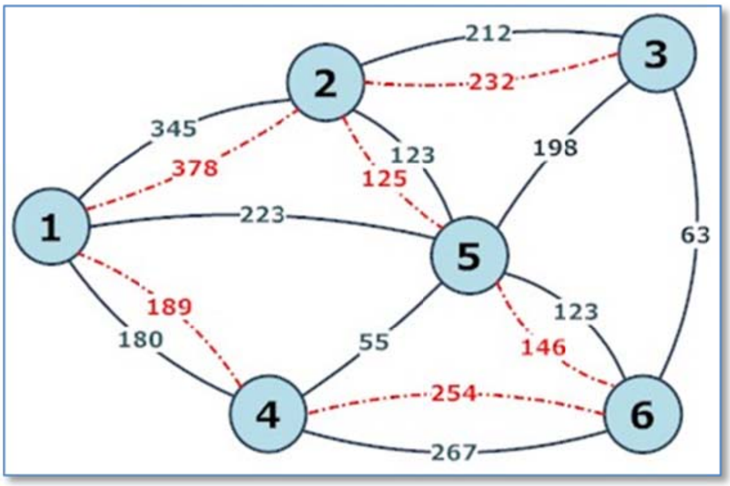

Figure 6.4: 6-nodes Network

6.1.3.2 12-node Network

Medium size network was extended to 18 nodes network. The total length of roads is 3,273 km and the length of rails was extended to 2,578 km. The network design is shown on Figure 6.5.

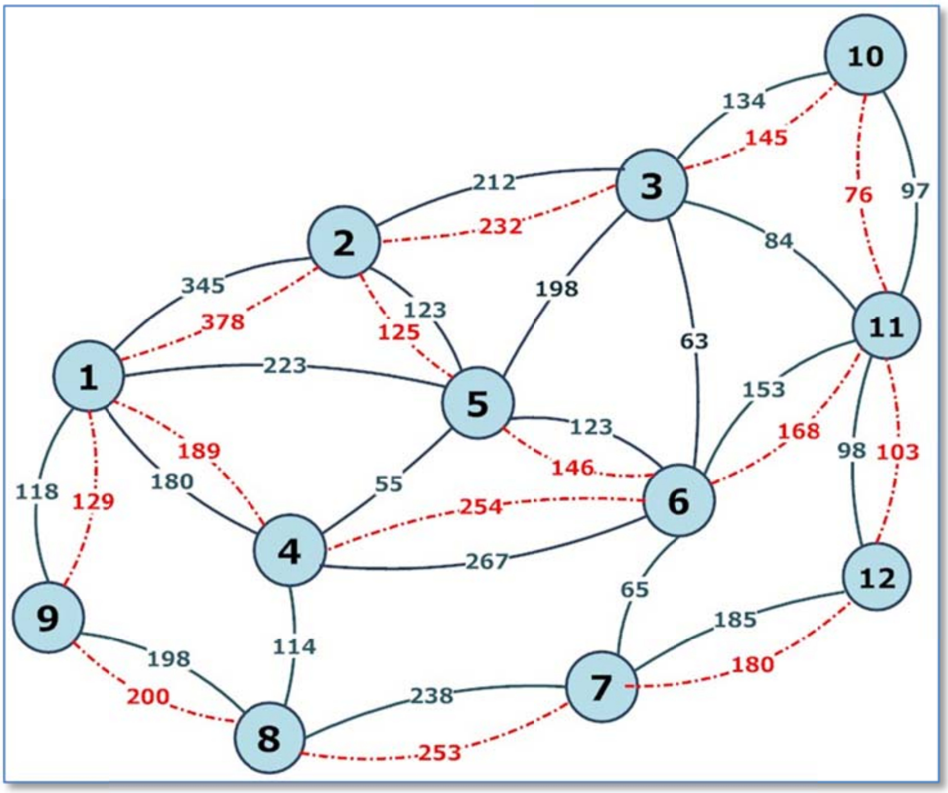

Figure 6.5: 12-nodes Network

6.1.3.3 18-node Network

The biggest test network is composed of 18 nodes that are interconnected by 4,804 km of roads and 3,222 km of rails. The 36-node network is illustrated on Figure 6.6.

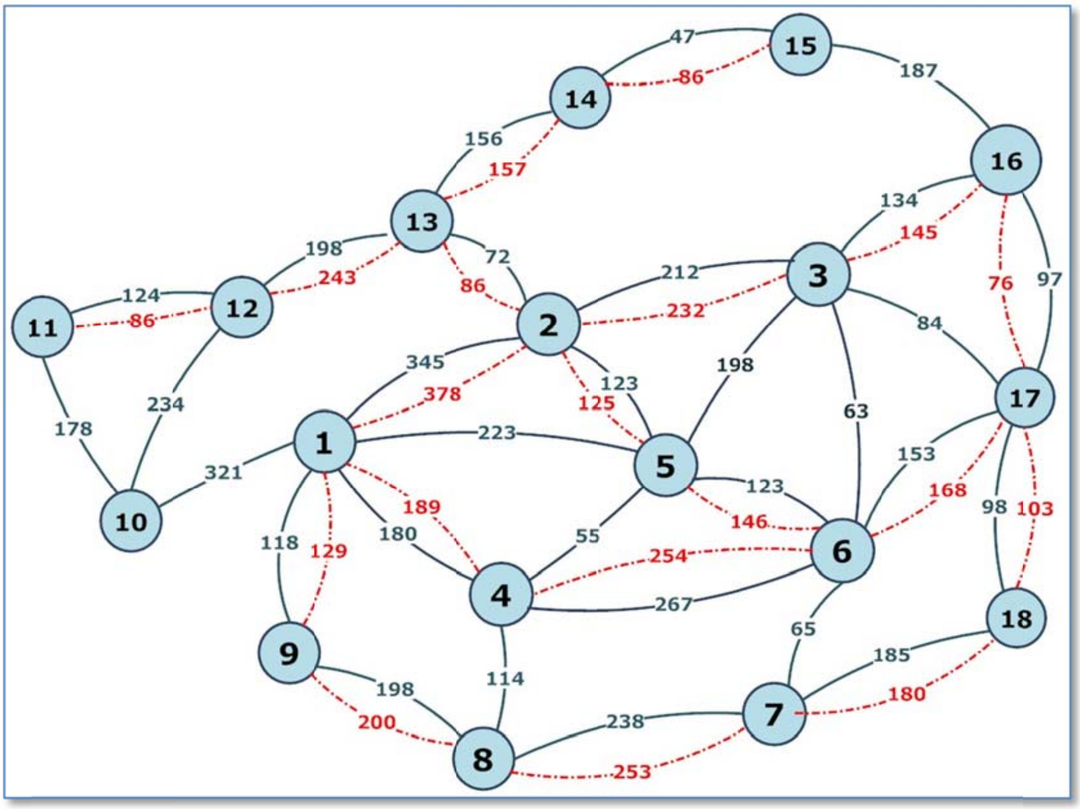

Figure 6.6: 18-nodes Network

6.1.4 Demand

The demand matrix represents the number of trailers (containers) shipped by the system in one year. The values were generated randomly between 1000 and 2000 units per year. The experiments consider three carriers of interest and one type of commodity.

The demand is defined as a combination of commodity and a carrier. That is why another two matrices are defined to identify the origin and destination nodes of each commodity. In this model five carriers and several types of commodities are considered.

6.1.5 Cost matrix to establish a facility as an intermodal collaborative facility

This matrix represents the costs to establish a facility as an intermodal collaborative facility for each carrier. The values vary from the fixed element of calculated transfer cost in

equation 3.3. The values were randomly generated from 200,000 Euros and 400,000 Euros per year.

6.1.6 Matrix of rail capacities

Each established multimodal collaborative facility has a capacity limitation. Therefore, the limit of passing units per year for each node in the network is defined.

In contrast to previous models, there is defined a set of 5 train operators that offer their train capacity to carrier. The train capacity is not defined just for each node in the network but, for each combination of arc and train operator.

6.2 Computational resources

The computing environment consists of a IBM Lenovo ThinkPad T61 with Intel® Core™2 Duo CPU processor under the Windows 7 64-bit Ultimate operating system with 4 GB of RAM. The server device with 2 X5680 3,33 GHz processors of Intel® Xeon® CPU under Windows 7 64-bit Enterprise operating system with 8 GB of RAM was used for more complex processes. The GAMS/CPLEX version 22.9.2 was used.

6.3 Experiments setup

There are 4 possible collaboration scenarios in experiments that are illustrated on Figure 6.7. The collaboration route can take whole route if $i=l$ and $j=m$. This case is shown on illustration A. The rail mode of transportation is used through the whole route. The collaborative route will take place most likely in the middle of the route; this case is illustrated in C. The last combination is shown on illustrations D and F. The collaborative portion takes place either at the beginning of the route or at the end. The condition that $i=l$ or $j=m$ must be satisfied. B illustrates the non-collaborative route.

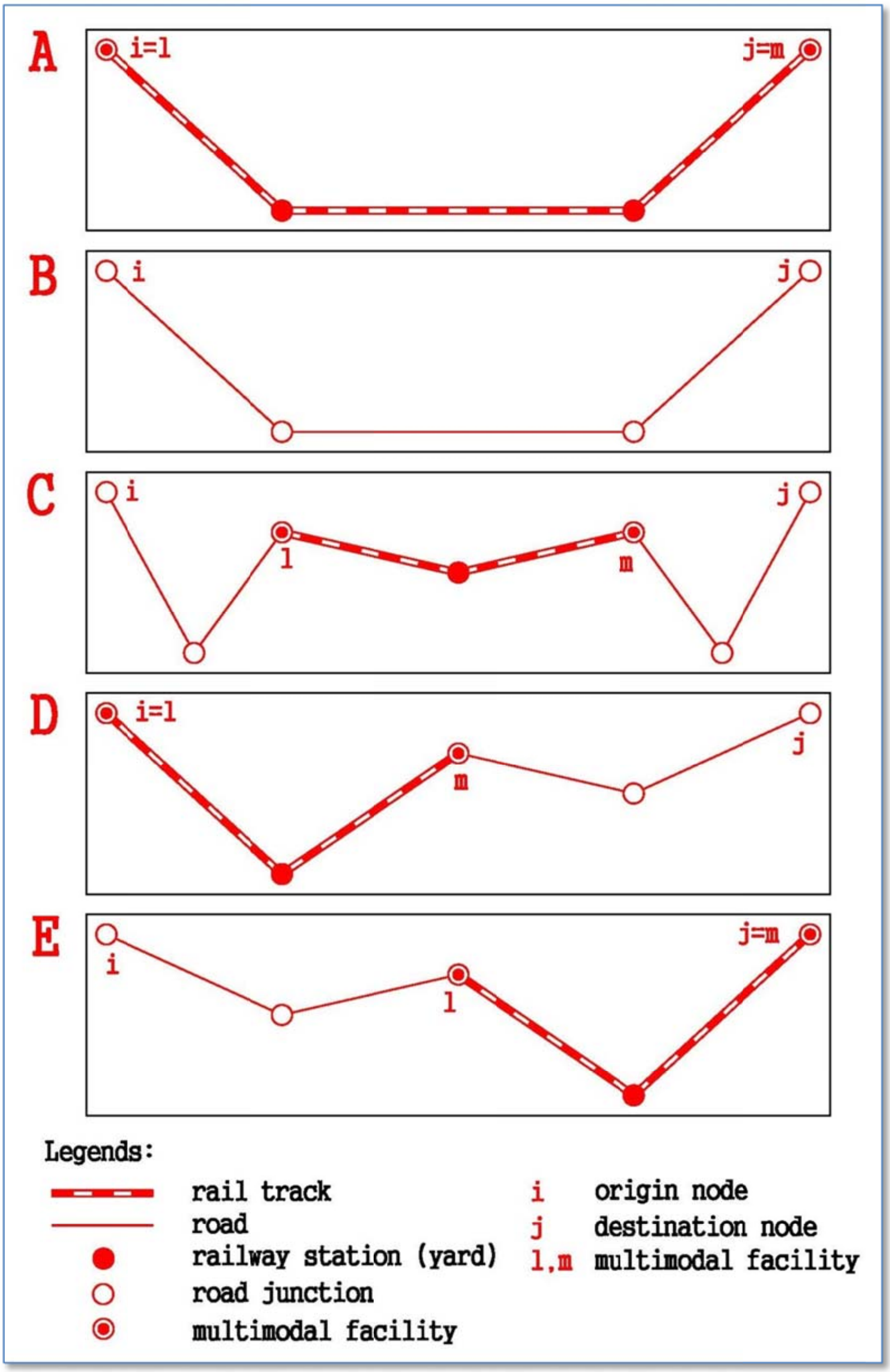

Figure 6.7: The collaboration scenarios

6.4 Experiments

The potential for collaboration among multimodal network is investigated by focusing on the level of monetary savings due to the collaboration. The level of collaboration is reflected through the number of established multimodal facilities, which takes values from 0 to the value when the total costs start to go up. On the basis of the calculations, one can determine the best allocations of multimodal facilities and their optimal number. The following sections highlight the results under varying network conditions.

6.4.1 6 node network hub location experiment

As seen in Table 6.7, the total costs decrease even when two facilities are established. However, the value of objective function increases if 4 or more hubs are established. This is caused by increasing costs to establish multimodal facilities that exceed savings from collaboration. Costs performance is illustrated in Figure 6.8. The optimal solution for 6-node network is establishing 3 multimodal facilities in nodes 2, 4, and 5 as is illustrated in Figure 6.9. The costs structure of optimal solution is shown on Figure 6.10.

Table 6.7: The Comparison of different scenarios of number of established facilities in 6-node network

No. of located facilities	Locations	Costs to establish transfer facilities [€]	Non-collaborative costs [€]	Collaborative costs[€]	Total costs [€]	Cost improvement	CPU time [s]
No collaboration		0.00	19,685,809.00	0.00	19,685,809.00		0.10
2	2,4	1,400,315.00	9,063,489.00	4,540,001.00	15,003,805.00	23.78 %	1.04
3	2,4,5	2,173,433.00	5,748,154.00	6,278,979.00	14,200,566.00	5.35 %	1.46
4	1,2,4,5	3,049,365.00	3,093,446.00	8,207,928.00	14,350,739.00	-1.06 %	0.48
5	1,2,4,5,6	3,963,291.00	1,821,155.00	9,412,784.00	15,197,230.00	-5.90 %	0.59
6	1,2,3,4,5,6	4,942,883.00	1,364,001.00	9,853,660.00	16,160,544.00	-6.34 %	0.15

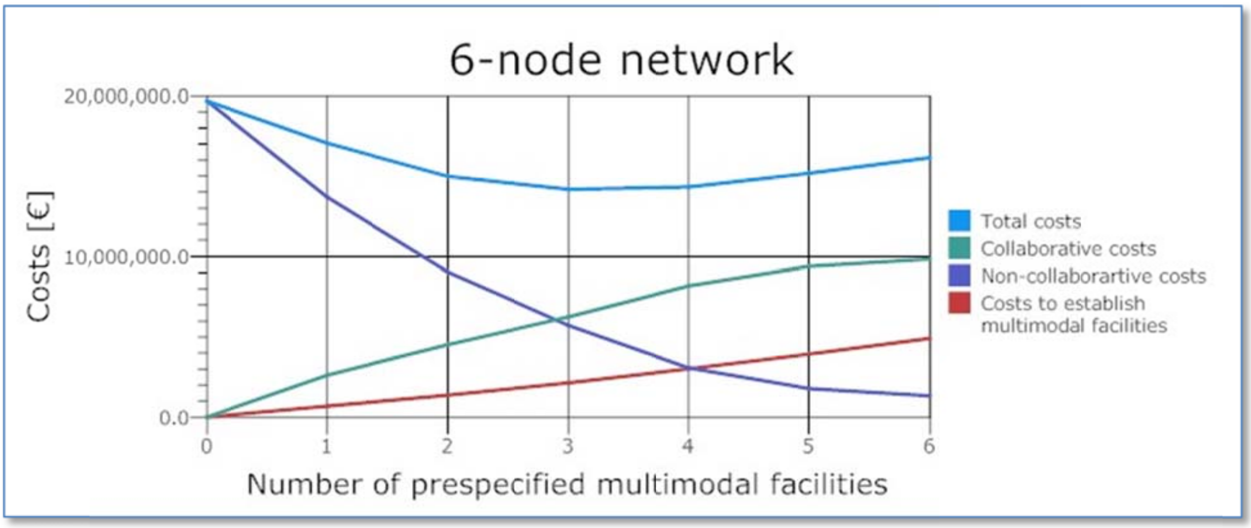

Figure 6.8: The comparison of the costs performance for 6-node network

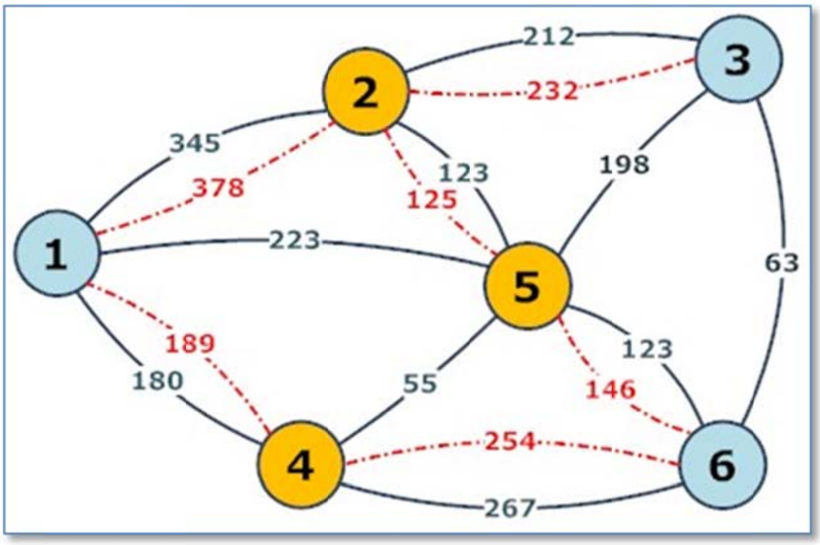

Figure 6.9: The optimal location of 3 multimodal facilities in 6-node network

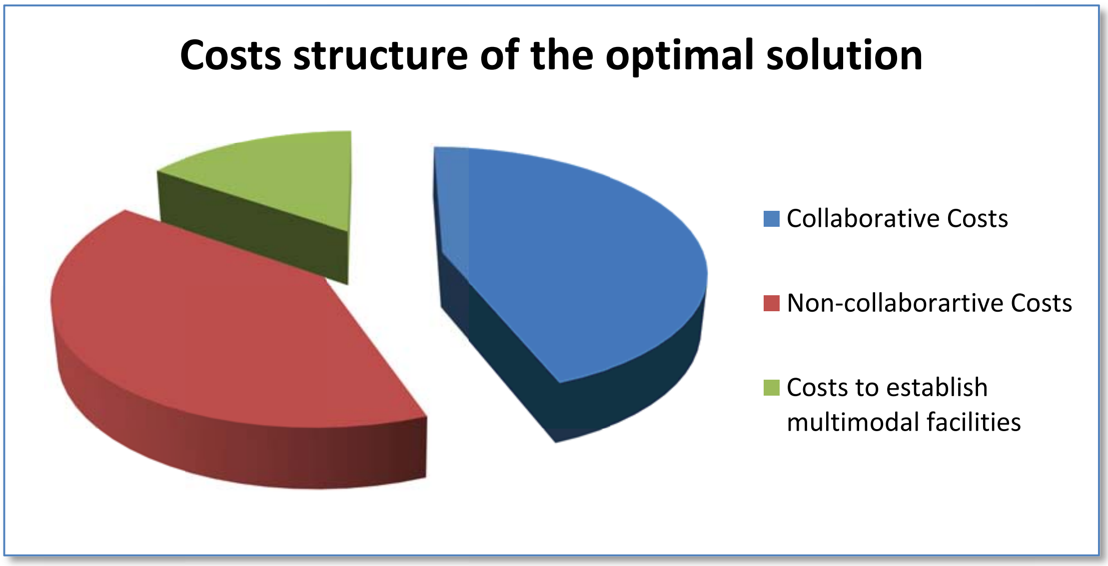

Figure 6.10: The costs structure of the optimal solution in 6-node network

6.4.2 12 node network hub location experiment

The optimal solution in 12-node network is 6 multimodal facilities. The costs performance is listed in Table 6.8 and illustrated in Figure 6.11. The collaborative costs and non-collaborative costs become constant after 7 or more facilities are established. This is caused

either by utilization of all available rail capacity or the possibility of effective use of collaborative routes between specific O-D pairs. The optimal locations of hubs are in nodes 1,2,6,8,10 and 12 as illustrated in Figure 6.12. The costs structure of this solution is shown on Figure 6.13.

Table 6.8: The comparison of different scenarios of number of established facilities in 12-node network

No. of located facilities	Locations	Costs of establishing the transfer facility [€]	Non-collaborative costs [€]	Collaborative costs [€]	Total costs [€]	Cost improvement	CPU time [s]
No collaboration		0.00	37,527,848.00	0.00	37,527,848.00		1.99
2	1,6	1,586,626.00	24,164,555.00	5,814,052.00	31,565,233.00	15.89%	35.36
3	1,6,8	2,432,510.00	18,904,777.00	8,023,174.00	29,360,461.00	6.98%	24.02
4	1,2,6,8	3,430,021.00	14,046,485.00	10,551,598.00	28,028,104.00	4.54%	56.23
5	1,2,6,8, 12	4,215,889.00	10,858,606.00	11,890,199.00	26,964,694.00	3.79%	41.75
6	1,2,6,8, 10,12	5,005,579.00	8,128,872.00	13,008,931.00	26,143,382.00	3.05%	36.46
7	1,2,5,6,8, 10,12	5,849,413.00	4,468,932.00	16,244,723.00	26,563,068.00	-1.61%	6.47
8	1,2,5,6,8, 9,10,12	6,681,167.00	4,468,932.00	16,244,721.00	27,394,820.00	-3.13%	7.94
9	1,2,3,5,6, 8,9,10,12	7,548,370.00	4,468,932.00	16,244,722.00	28,262,024.00	-3.17%	9.92
10	1,2,3,4,5, 6,8,9,10,12	8,747,506.00	15,626,878.00	18,361,043.00	29,207,844.00	-1.78%	184.74

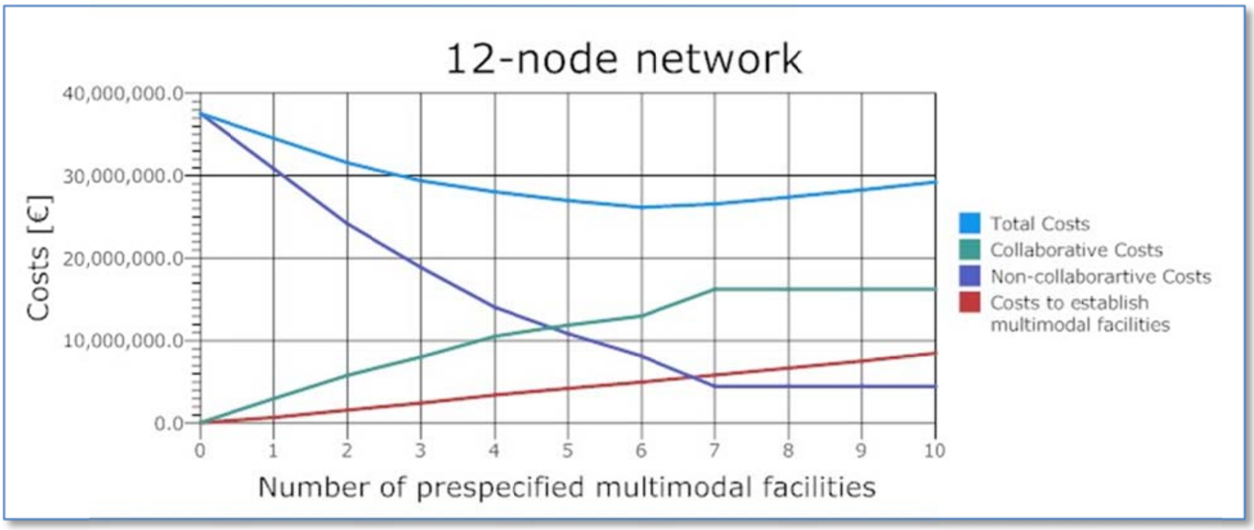

Figure 6.11: The comparison of the costs performance for 12-node network

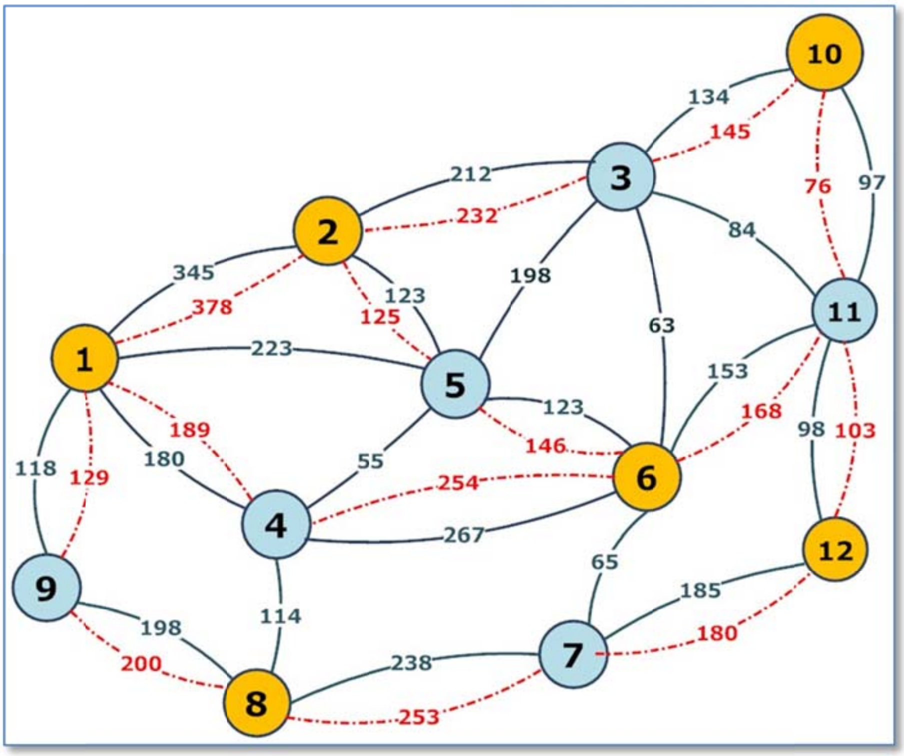

Figure 6.12: The optimal location of 6 multimodal facilities in 12-node network

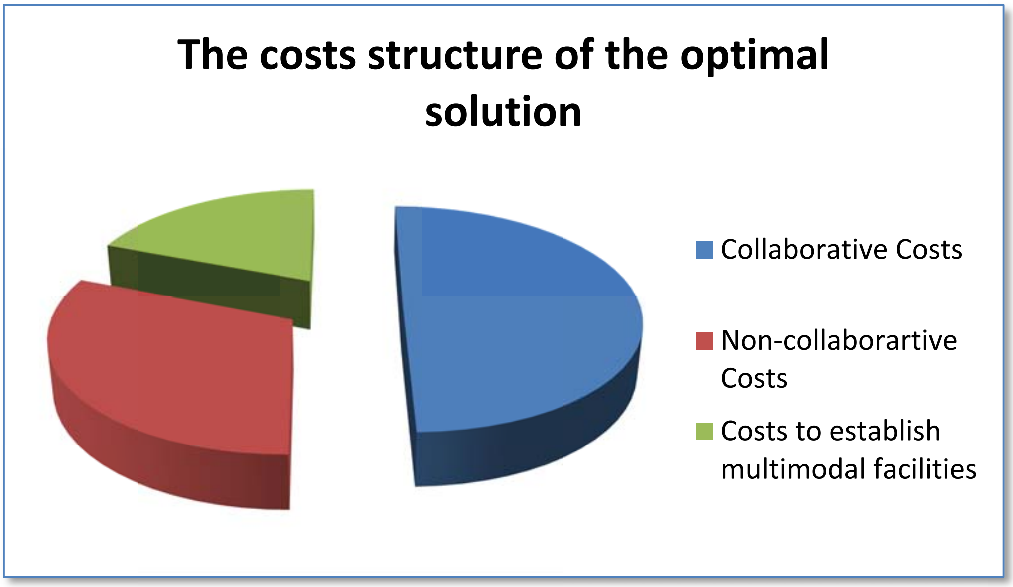

Figure 6.13: The costs structure of the optimal solution in 12-node network

6.4.3 18 node network hub location experiment

Table 6.9 illustrates the results of the costs performance for the 18-node network by locating specific numbers of multimodal facilities. The lowest total costs are reached if 8 hubs are established in this network. The allocation of optimal solution is in nodes 1,2,6,8,11,13.16 and 18. The graphical representation is illustrated in Figure 6.15. As shown in Figure 6.14, the collaborative and non-collaborative costs become constant after 9 or more facilities are established. Thereafter the total costs depend only on marginal cost to establish other multimodal facility. Final costs structure of best solution is shown on Figure 6.16. Just a note, since the problem is NP-hard the less the number of facilities needed to be established the greater the computational expense was observed. This is due to greater number of combinations of possible sites.

Table 6.9: The comparison of different scenarios of number of established facilities in 18-node network

No. of located facilities	Locations	Costs of establishing the transfer facility [€]	Non-collaborative costs [€]	Collaborative costs [€]	Total costs [€]	Improvement	CPU time [s]
No collaboration		0.00	54,714,761.00	0.00	54,714,761.00		25.77
2	2,6	1,933,546.00	39,952,709.00	6,381,513.00	48,267,768.00	11.78%	31802.55
3	2,6,13	2,850,262.00	34,360,859.00	9,103,028.00	46,314,149.00	4.05%	4633.41
4	2,6,7,13	3,796,727.00	29,693,983.00	11,057,023.00	44,547,733.00	3.81%	2272.39
5	1,2,6,7,13	4,596,465.00	23,078,624.00	15,218,020.00	42,893,109.00	3.71%	809.57
6	1,2,6,8,13,18	5,464,323.00	20,034,307.00	16,508,921.00	42,007,551.00	2.06%	723.96
7	1,2,6,8,13,16,18	6,413,510.00	17,344,362.00	17,597,705.00	41,355,577.00	1.55%	423.48
8	1,2,6,8,11,13,16,18	7,203,737.00	16,069,206.00	17,993,130.00	41,266,073.00	0.22%	278.99
9	1,2,6,8,11,13,14,16,18	7,999,221.00	15,626,878.00	18,361,043.00	41,987,142.00	-1.75%	331.32
10	1,2,6,7,9,11,13,14,16,18	8,747,506.00	15,626,878.00	18,361,043.00	42,735,427.00	-1.78%	184.74

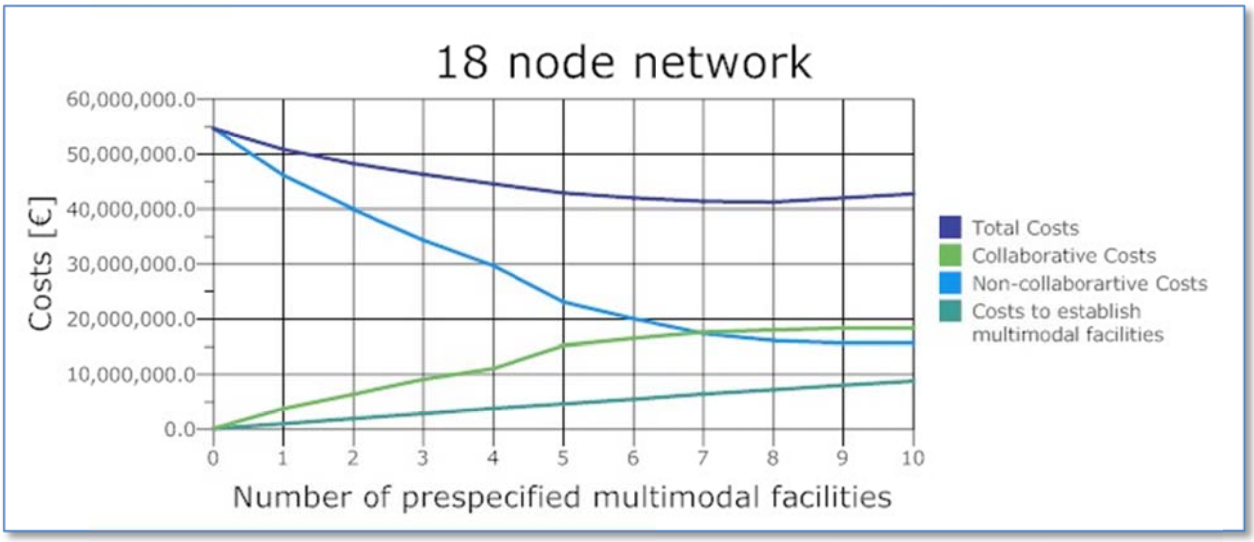

Figure 6.14: The comparison of the costs performance for 18-node network

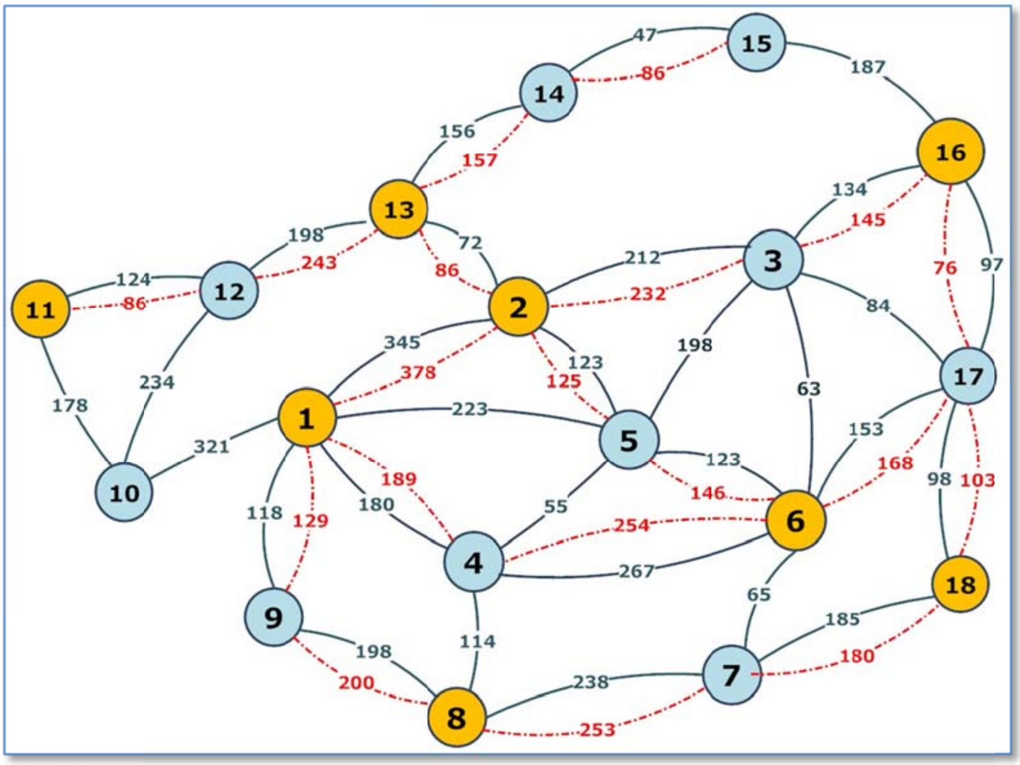

Figure 6.15: The optimal locations of 8 multimodal facilities in 18-node network

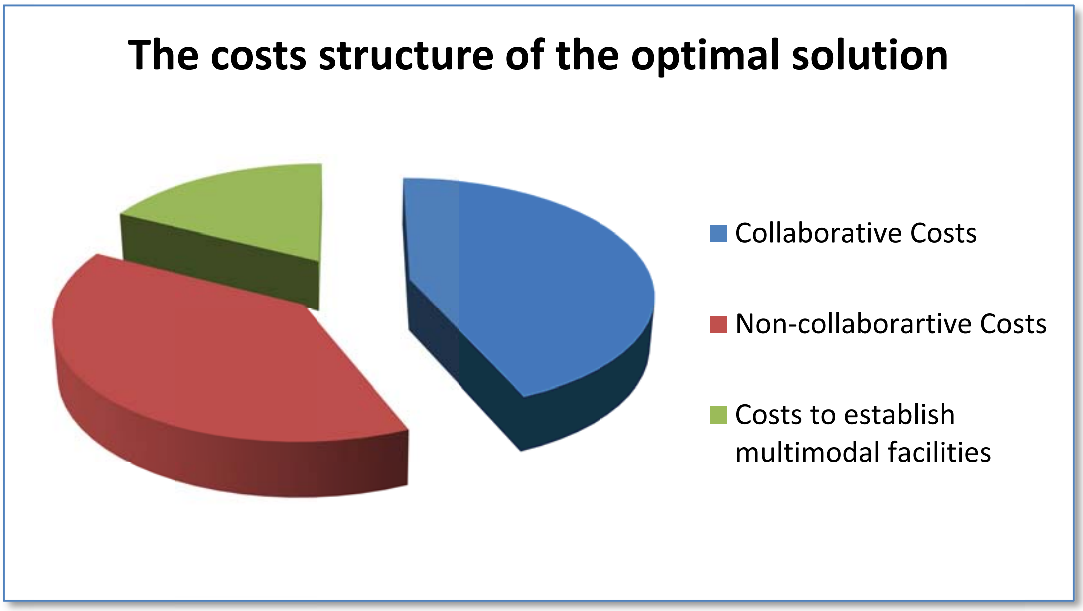

Figure 6.16: The costs structure of the optimal solution in 18-node network

6.4.4 18 node network design experiment

The network design model was tested just on 18 node network; the reason is that we are interested in the viability of collaboration through rail-road collaborative routes. In future work we will consider larger networks and the issue of time-dependency. The experiment considers 5 carriers of interest and 5 collaborative train operators. This generates the possible combinations of 2^5 collaborative pairs. The experiments were run with varying number of shipments from 20, 40, 60, respectively. The total costs and composition of collaborative and non-collaborative routes is listed in Table 6.10. These results are a snapshot of the network design analysis. The following sections we illustrate how collaborative rates can influences the routes taken and the costs to the collaborative.

Table 6.10: The comparison of different scenarios of network design demand in 18-node network

Number of shipments	Total Costs	Non-collaborative Costs	Collaborative Costs	Non-collaborative routes	Collaborative Routes	CPU time
20	8,939,864	2,134,944	6,804,920	14	46	1.592
40	16,965,753	3,871,062	13,094,691	28	92	3.697
60	26,987,520	7,324,932	19,662,588	43	137	7.145

6.5 Sensitivity Analysis

In this section a sensitivity analysis is performed. Sensitivity analyses illustrate how changes of certain input values (costs) produced due to inappropriate prediction or some other reason , influence certain criteria values and the total costs (Janovic, 1999). The sensitivity parameters are α (alpha), β (beta) and γ (gamma).

6.5.1 Collaborative discount rate for the MFCHLP problem

The sensitivity parameter α represents the discount rate of the collaborative part of route for the MFCHLP problem. The discount parameter was established in range between 0 (no

discount) and 0.9 (90% discount). Table 6.11 shows the results for parameter α case of optimal solution in 18-node network. This parameter can be represented in reality as a government subvention or as the saving from usage of more efficient technology (e.g. lower cost of depreciation or repair and maintenance costs). The graphical representation is shown in Figure 6.17. The analysis was performed for eight hubs (since 8 hubs were the optimal under default values). The results indicate a decrease in total costs as alpha increases.

Table 6.11: Sensitivity analysis of optimal solution in 18-node network for the MFCHLP problem according to parameter α

No. of hubs	Alpha	Locations	Collaborative Costs	Non-collaborative Costs	Costs of establishing the transfer facilities	Total Costs
8	0.0	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	7,203,737.00	41,266,072.00
	0.1	1,2,6,8,12,13,16,18	17,740,173.00	16,069,206.00	7,272,762.00	41,082,141.00
	0.2	1,2,3,6,8,12,13,18	16,281,518.00	17,209,563.00	7,297,064.00	40,788,145.00
	0.3	1,2,3,6,8,12,13,18	15,619,661.00	17,209,563.00	7,297,064.00	40,126,288.00
	0.4	1,2,3,6,8,12,13,18	14,957,802.00	17,209,563.00	7,297,064.00	39,464,429.00
	0.5	1,2,3,6,7,8,13,17	13,940,966.00	17,344,362.00	7,472,744.00	38,758,072.00
	0.6	1,2,3,6,7,8,13,17	13,209,623.00	17,344,362.00	7,472,744.00	38,026,729.00
	0.7	1,2,3,6,7,8,13,17	12,478,277.00	17,344,362.00	7,472,744.00	37,295,383.00
	0.8	1,2,3,6,7,8,13,17	11,746,929.00	17,344,362.00	7,472,744.00	36,564,035.00
	0.9	1,2,3,6,7,8,12,13	10,162,821.00	18,257,167.00	7,395,041.00	35,815,029.00

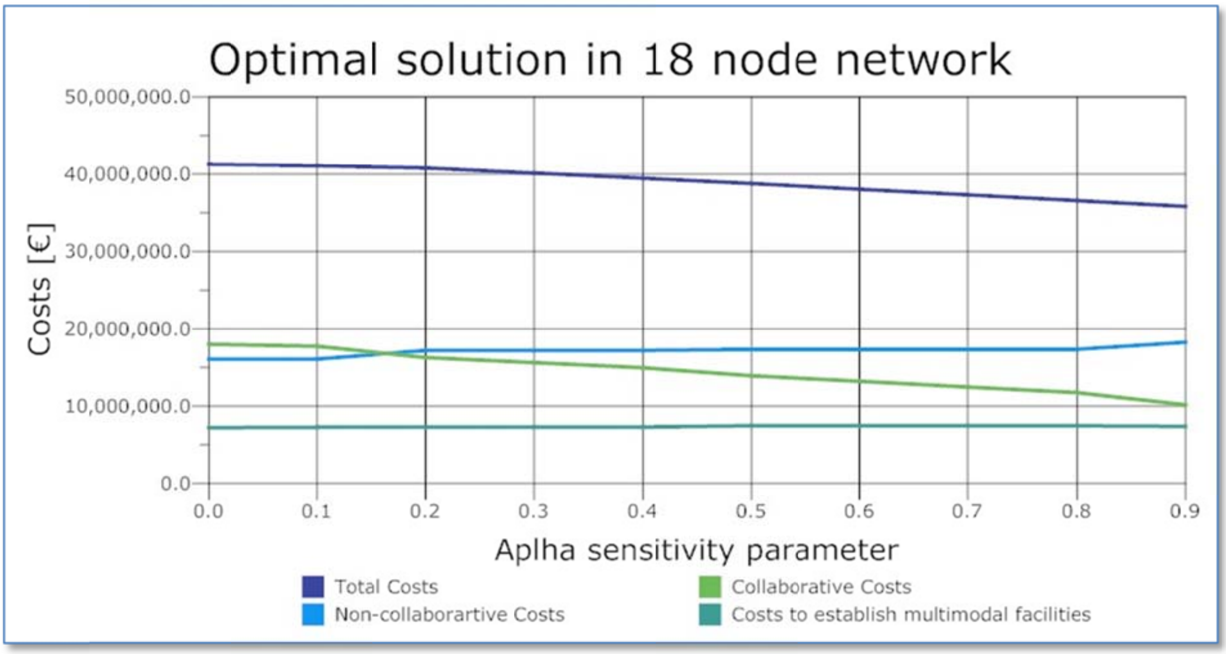

Figure 6.17: Costs performance according to sensitivity parameter α

6.5.2 Profit margin

6.5.2.1 Hub location model

The parameter β (see Equation 4.5) represents the profit margin expected by carrier in order to participate in the collaboration. Table 6.11 illustrates the costs variation according to different setup of parameters β. The tested range of this parameter was from 0.0 (no expected marginal profit) to 1.0 (100% marginal profit). As seen from the results, the carriers are less likely to collaborate if the marginal profit gets close to 100% and more likely if there is no expected marginal profit.

The performance of β parameter in 6-node network is listed in Table A-1 (see Appendix). The costs performance of optimal case with allocation of 3 facilities is illustrated in Figure 6.18 and the graphical representation of total costs for all possible combinations of number of located facilities is shown in Figure 6.19.

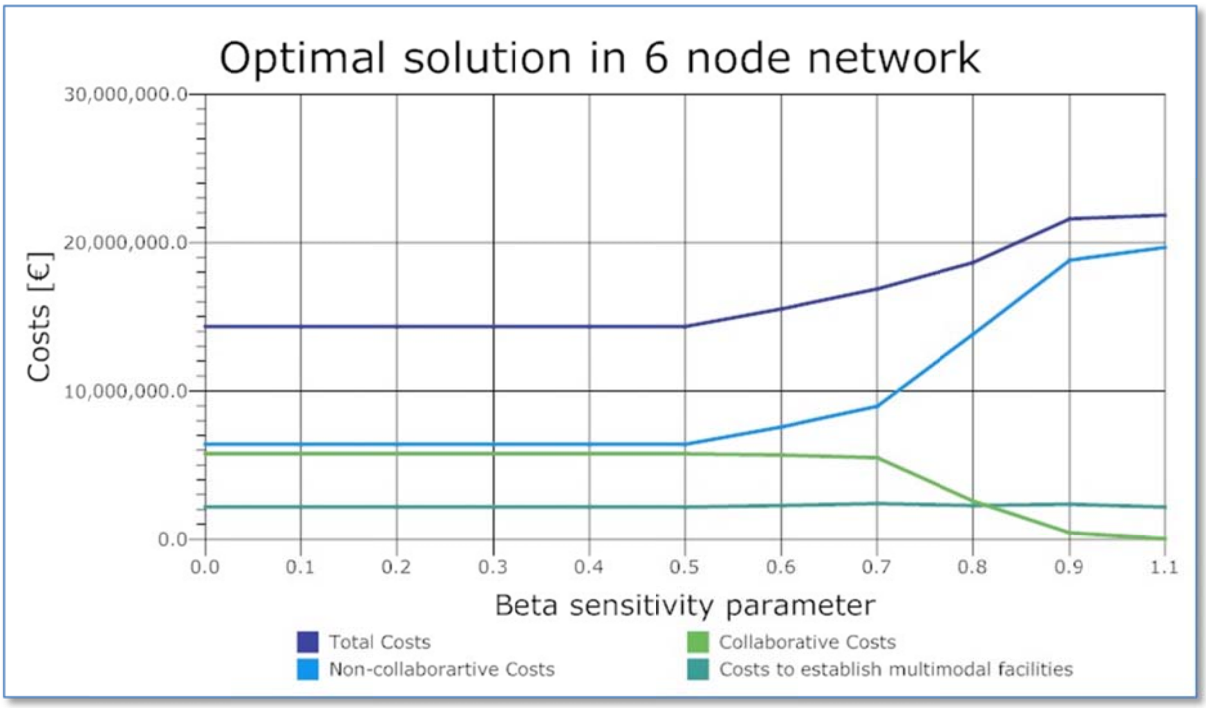

Figure 6.18: Costs performance in 6-node network according to sensitivity parameter β

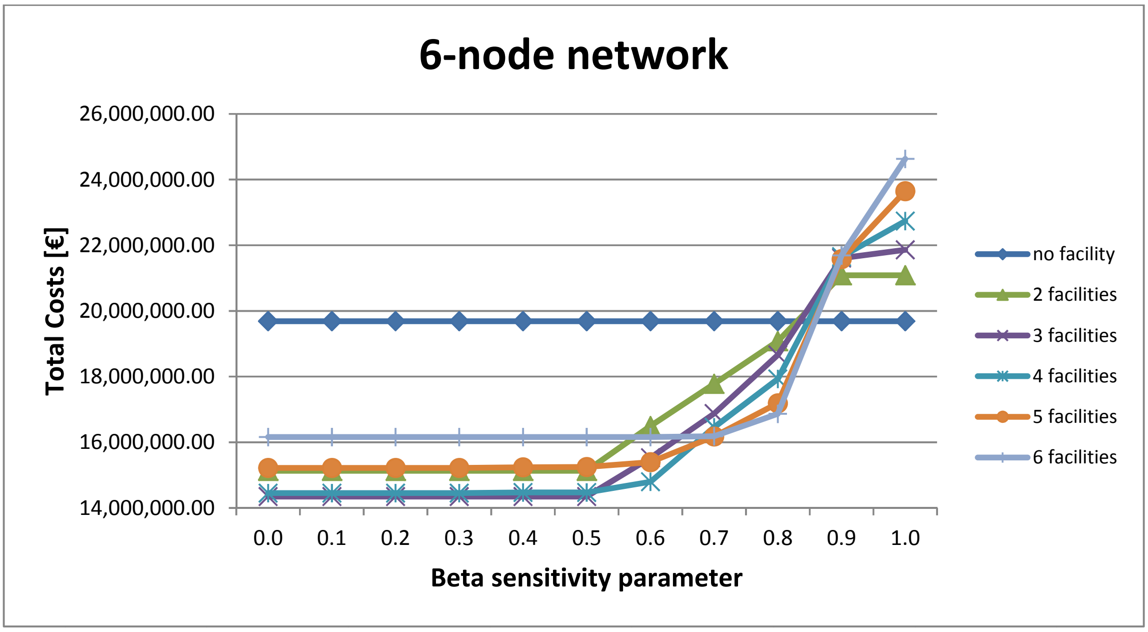

Figure 6.19: Total costs performance in 6-node network according to sensitivity parameter β

Table A-2 (see Appendix) illustrates the results of sensitivity analysis that was performed according to parameter β in 18-node network. Figure 6.20 shows the costs performance of optimal solution and Figure 6.21 illustrates the total costs of scenarios of allocation 7,8, and 9 facilities.

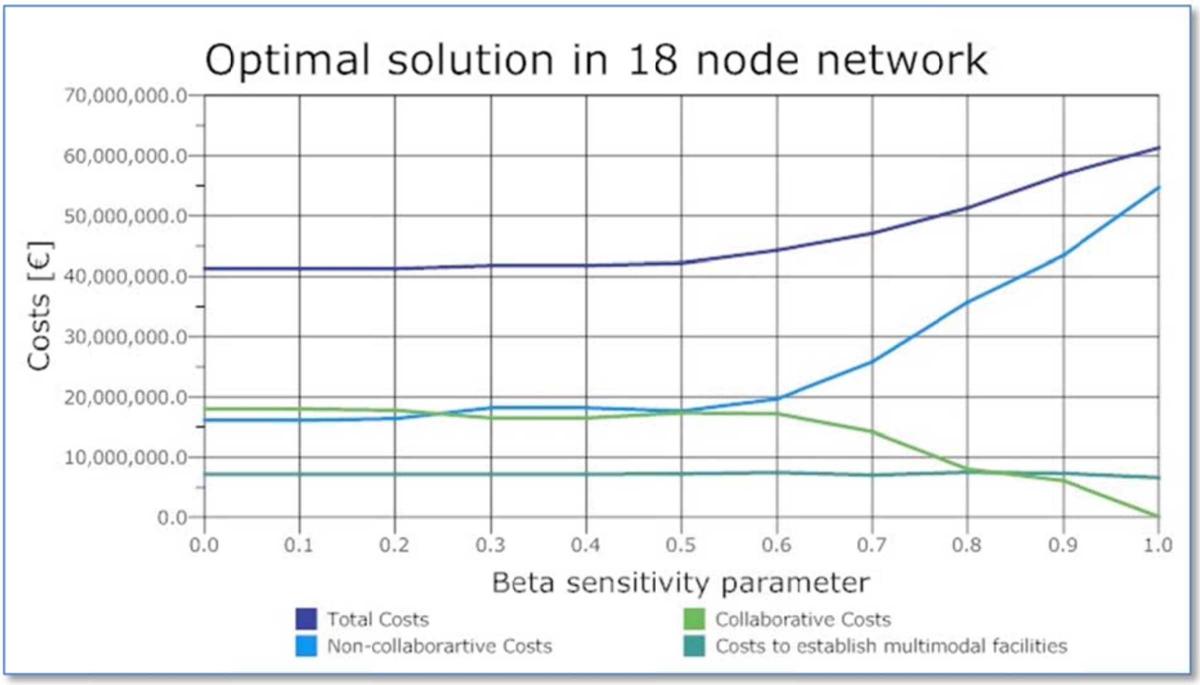

Figure 6.20: Costs performance in 18-node network according to sensitivity parameter β

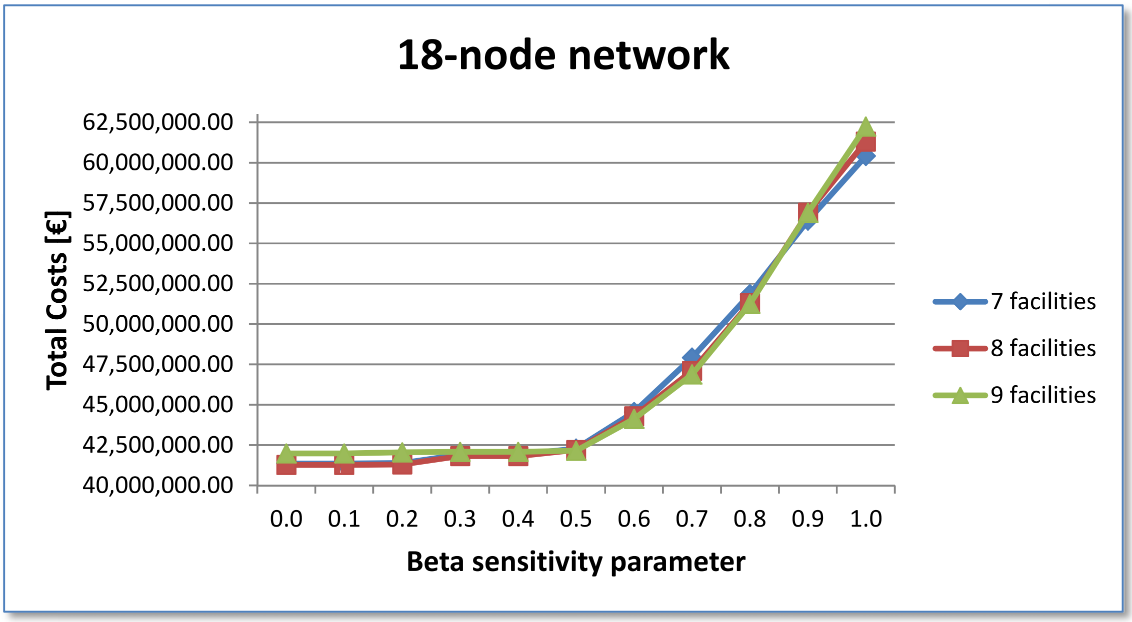

Figure 6.21: Total costs performance in 18-node network according to sensitivity parameter β

6.5.2.2 Network design model

The level of collaboration depends on marginal effect occurred by collaboration. Carriers focus its collaboration decision on possible level of monetary savings. Therefore the constraint representing the comparison of marginal profit (Equation 5.7) was integrated to the network design model. The parameter β takes values from 0 in 0.1 intervals up to 1.0. The costs calculation for all parameters is listed in Table 6.12. The graphical performance is illustrated in Figure 6.22. As seen in the results as the marginal profit decreases, the collaboration decreases as well. This is true for all cases.

Table 6.12: Sensitivity analysis of 18-node network design model according to parameter β

Number of shipments	β	Total Costs	Non-collaborative Costs	Collaborative Costs	Non-collaborative routes	Collaborative Routes	CPU time
	0.0	8,939,864.00	2,134,944.00	6,804,920.00	14	46	1.592
	0.1	8,939,864.00	2,134,944.00	6,804,920.00	14	46	1.544
	0.2	8,961,903.00	2,134,944.00	6,826,959.00	14	46	1.419
	0.3	9,333,978.00	3,480,596.00	5,853,382.00	24	36	1.139
	0.4	10,290,472.00	6,161,376.00	4,129,096.00	36	24	0.920
20	0.5	12,448,102.00	11,679,047.00	769,055.00	57	3	0.749
	0.6	12,650,251.00	12,650,251.00	0.00	60	0	0.702
	0.7	12,650,251.00	12,650,251.00	0.00	60	0	0.796
	0.8	12,650,251.00	12,650,251.00	0.00	60	0	0.718
	0.9	12,650,251.00	12,650,251.00	0.00	60	0	0.749
	1.0	12,650,251.00	12,650,251.00	0.00	60	0	0.686
	0.0	16,965,753.00	3,871,062.00	13,094,691.00	29	91	3.697
	0.1	16,965,753.00	3,871,062.00	13,094,691.00	29	91	3.432
	0.2	17,054,055.00	4,183,356.00	12,870,699.00	32	88	3.775
	0.3	17,676,720.00	6,535,918.00	11,140,802.00	50	70	2.683
	0.4	19,647,448.00	12,774,924.00	6,872,524.00	78	42	1.966
40	0.5	23,034,738.00	21,491,333.00	1,543,405.00	112	8	1.701
	0.6	23,297,140.00	23,297,140.00	0.00	120	0	1.451
	0.7	23,297,140.00	23,297,140.00	0.00	120	0	1.466
	0.8	23,297,140.00	23,297,140.00	0.00	120	0	1.466
	0.9	23,297,140.00	23,297,140.00	0.00	120	0	1.420
	1.0	23,297,140.00	23,297,140.00	0.00	120	0	1.341
	0.0	26,987,520.00	7,324,932.00	19,662,588.00	43	137	7.145
	0.1	26,987,520.00	7,324,932.00	19,662,588.00	43	137	6.568
	0.2	27,194,303.00	8,248,732.00	18,945,571.00	51	129	6.349
	0.3	28,236,449.00	12,241,568.00	15,994,881.00	81	99	4.727
	0.4	30,979,235.00	19,462,233.00	11,517,002.00	115	55	3.573
60	0.5	35,706,925.00	33,690,318.00	2,016,607.00	172	8	2.387
	0.6	36,267,729.00	36,267,729.00	0.00	180	0	2.184
	0.7	36,267,729.00	36,267,729.00	0.00	180	0	2.121
	0.8	36,267,729.00	36,267,729.00	0.00	180	0	2.137
	0.9	36,267,729.00	36,267,729.00	0.00	180	0	2.434
	1.0	36,267,729.00	36,267,729.00	0.00	180	0	2.106

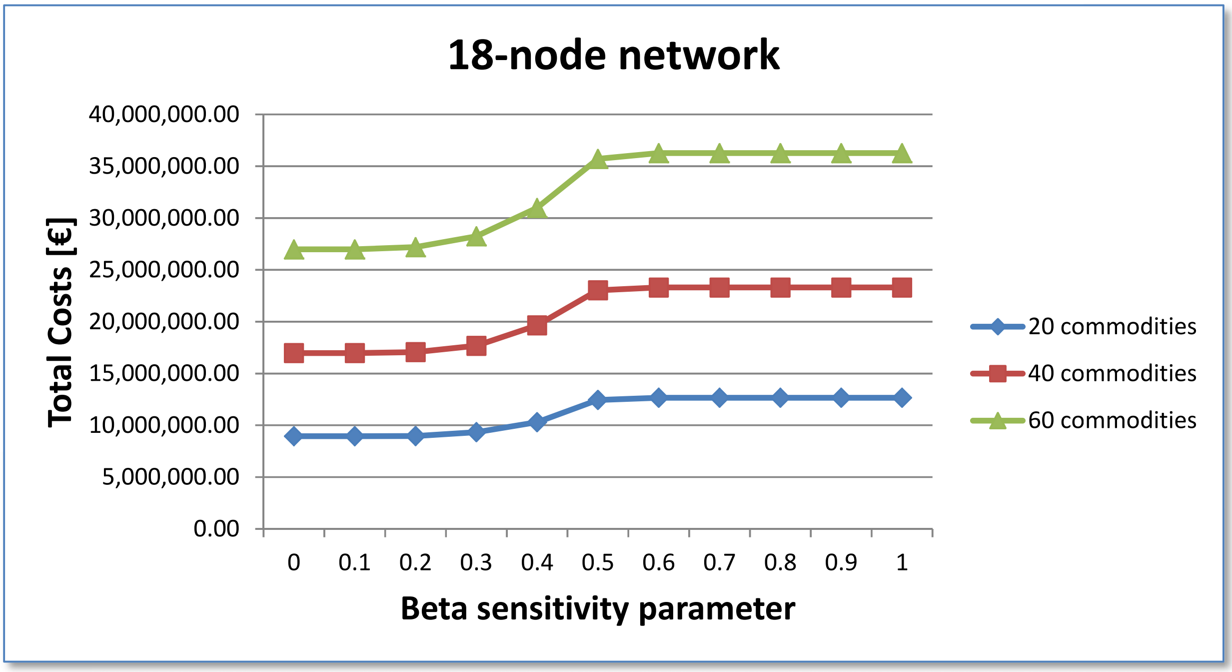

Figure 6.22: Total costs performance in 18-node network design model according to sensitivity parameter β

6.5.3 Facility establishment discount rate

Similar to the collaborative discount rate parameter, the facility establishment discount rate parameter was created. This parameter represents the discount of annual costs of locating a multimodal facility at candidate sites. The differences in costs according to γ are discussed in Table 6.13. Figure 6.23 plots the relationship between costs and the value of γ parameter. The results indicated the linear dependency of total costs on costs of establishing transfer facilities.

Table 6.13: Sensitivity analysis of 18-node network according to parameter γ

No. of hubs	Gamma	Locations	Collaborative Costs	Non-collaborative Costs	Costs of establishing the transfer facilities	Total Costs
	0.0	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	7,203,737.00	41,266,072.00
	0.1	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	6,483,364.00	40,545,699.00
	0.2	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	5,762,986.00	39,825,321.00
	0.3	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	5,042,614.00	39,104,949.00
	0.4	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	4,322,241.00	38,384,576.00
8	0.5	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	3,601,876.00	37,664,211.00
	0.6	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	2,881,496.00	36,943,831.00
	0.7	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	2,161,123.00	36,223,458.00
	0.8	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	1,440,751.00	35,503,086.00
	0.9	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	720,373.00	34,782,708.00
	1.0	1,2,6,8,11,13,16,18	17,993,129.00	16,069,206.00	0.00	34,062,335.00

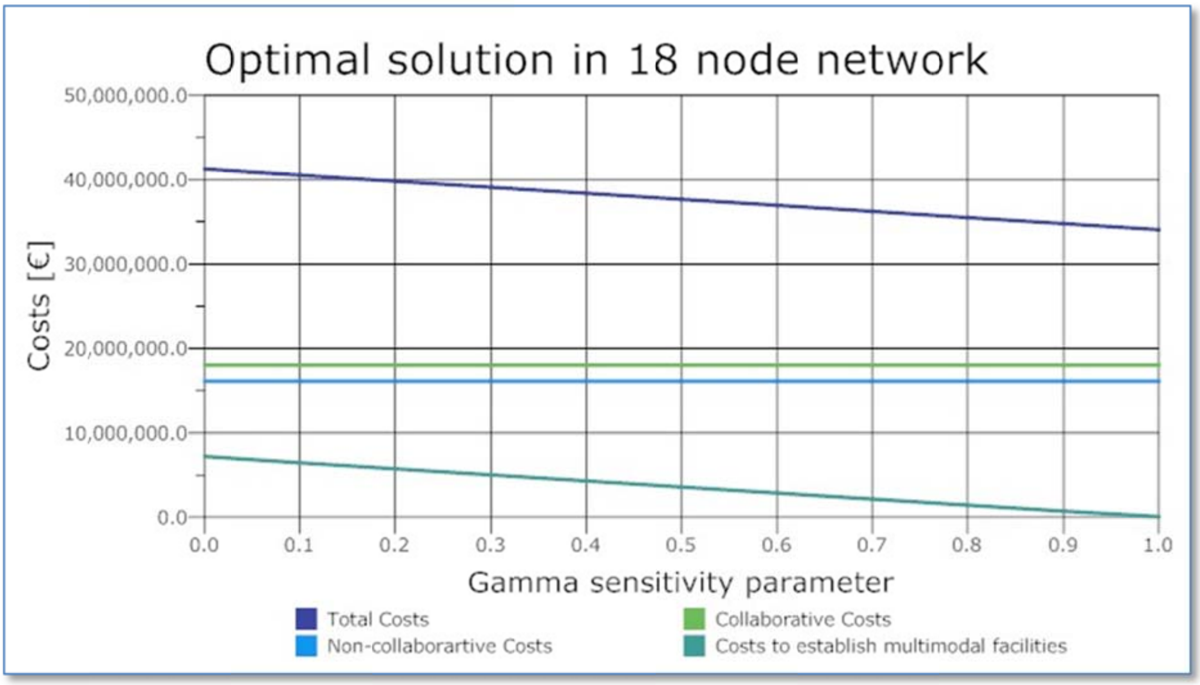

Figure 6.23: Costs performance in 18-node network according to sensitivity parameter γ

6.6 Summary

In this chapter, an applications of a multimodal freight collaborative hub location problem and a collaborative freight multimodal fixed charged network design problem were presented. The numerical properties were observed through the different setting of scenarios. The problems were solved for several specific sizes of networks and different values of demand. In the sensitivity analysis, dependency of costs performance on several sensitivity parameters was investigated. Together both these models present a framework to study the viability of rail-road collaboration. Although the models differ in data inputs and mathematical structure, the results indicate that collaboration can reduce transport costs when there are several collaborating entities compared to shipping directly. The sensitivity analyses provide additional evidence of the potential of rail-road collaboration.

Chapter 7: CONCLUSIONS

This chapter summarizes concluding comments on the research performed, highlights its contributions, and proposes possible directions for future research. Section 7.1 gathers the researched finding and discusses the achieved insights. Section 7.2 discusses the contributions of the thesis, and Section 7.3 introduces possible extensions of proposed work in future research.

7.1 Summary

The study presents an analytical framework to explore the rail-road collaborative paradigm. Two mathematical models that seek to minimize the transportation costs are formulated. The MFCHLP identifies the optimal locations to establish the multimodal facilities in network. SMMCCP seeks to minimize the cost by selecting the most effective routing in a network. The potential application of models is demonstrated on several experiment. The costs benefits of collaboration are illustrated in these application. The sensitivity analysis explores the dependency of total costs on several parameters. The relation of collaboration level and total costs provides the carriers likelihood to collaborate. The degree of collaboration is explored also by collaborative discount rate and discount of transfer facilities establishing. The capacities of transfer facilities and trains can be optimized according to gained results, and possibly could be increased or decreased.

7.2 Contributions of the Thesis

The presented optimization of number of established multimodal facilities in collaborative network and efficient routing through network are examples of utilization of mathematical methods in transportation sciences.

The overall contributions could be summarized in following points:

1) Introduction of current state of rail-road collaboration. There was identified a gap in rail-road collaboration network optimization research that this study tries to fulfill.
2) The review of developed mathematical models related to our issue.
3) The new progressive rail-road technologies were discussed.
4) New mathematical formulation for transportation costs calculation were developed. These methodologies allow covering all cost components that affect the calculation of marginal costs of transportation.
5) The multimodal freight collaborative hub problem was formulated. The model finds the optimal locations of transfer facilities in network to minimize total costs of system.
6) The static multimodal collaborative problem also offers and interesting optimization tool. In contrast to previous model, this model tries to find the most effective routing in the network instead of finding the locations of transfer facilities.
7) The sensitivity analysis provides insights of level of collaboration. It was found that the level of collaboration directly depends on expected profit margin.

According to extensiveness of this problem, just the basic points were provided in optimization process. There are many other dimensions that can be included in models and increase the level of realism. This is indeed a part of our future research.

7.3 Future Research

The developed multimodal location and network design models are powerful tools for collaborative transportation pre-planning process but are not fully realistic in situations when the collaboration among transportation modes is already processed. This is a limitation in the static concept of presented models. The dynamic models could offer much more reliable and realistic analysis of collaborative network. The dynamic models cover also the time factor in transportation, which allows not only to find the most effective use of a network with minimal

costs but also the most effective use of network with minimal travel time. The development of dynamic modification of multimodal location and routing problem will be proposed to address this issue as a part of our future research.

In future research, the multimodal collaboration issue can be extended to address the collaborative paradigm of all modes of freight transportation, including also the air and maritime transportation. The specific application of collaborative transportation model can be applied in pipeline transportation. Pipeline transportation in form of transportation of fuel products presents the complex system that uses all modes of transportation except the air mode.

The developed costs calculation methodologies, that are proposed in our work, cover only the costs that take place among the market mechanism. Transportation phenomena also produces the costs to which the operators are not responsible and they do not have to pay the full costs of their activities. These costs are called externalities in transportation. They represent the negative effect of transportation such as emissions, noise, congestions, traffic accident, pollution, etc. Future research should include in its hypothesis also these elements.

From the environmental point of view, the transportation is often known as the biggest source of pollution. Another modification of our research offers the elimination of these negative effects of transportation phenomena by proper use of environmentally friendly modes of transportation. Future research of this issue could deal with minimization of the negative impacts caused by transportation.

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APPENDIX

Table A-1: Sensitivity analysis of 6-node network according to parameter β

No. of hubs	Beta	Locations	Collaborative Costs	Non-collaborative Costs	Costs of establishing the transfer facilities	Total Costs
0	0		0.00	19,685,809.00	0.00	19,685,809.00
	10		0.00	19,685,809.00	0.00	19,685,809.00
	20		0.00	19,685,809.00	0.00	19,685,809.00
	30		0.00	19,685,809.00	0.00	19,685,809.00
	40		0.00	19,685,809.00	0.00	19,685,809.00
	50		0.00	19,685,809.00	0.00	19,685,809.00
	60		0.00	19,685,809.00	0.00	19,685,809.00
	70		0.00	19,685,809.00	0.00	19,685,809.00
	80		0.00	19,685,809.00	0.00	19,685,809.00
	90		0.00	19,685,809.00	0.00	19,685,809.00
	100		0.00	19,685,809.00	0.00	19,685,809.00
2	0	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	10	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	20	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	30	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	40	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	50	2,4	4,468,118.00	9,261,619.00	1,400,315.00	15,130,052.00
	60	1,4	3,864,023.00	11,075,943.00	1,552,969.00	16,492,935.00
	70	1,4	3,771,418.00	12,454,737.00	1,552,969.00	17,779,124.00
	80	1,2	1,764,522.00	15,714,170.00	1,599,210.00	19,077,902.00
	90	2,4	0.00	19,685,809.00	1,400,315.00	21,086,124.00
	100	2,4	0.00	19,685,809.00	1,400,315.00	21,086,124.00
3	0	2,4,5	5,766,951.00	6,403,753.00	2,173,433.00	14,344,137.00
	10	2,4,5	5,766,951.00	6,403,753.00	2,173,433.00	14,344,137.00
	20	2,4,5	5,766,951.00	6,403,753.00	2,173,433.00	14,344,137.00
	30	2,4,5	5,766,951.00	6,403,753.00	2,173,433.00	14,344,137.00
	40	2,4,5	5,766,951.00	6,403,753.00	2,173,433.00	14,344,137.00
	50	2,4,5	5,768,495.00	6,403,753.00	2,173,433.00	14,345,681.00
	60	1,2,4	5,679,439.00	7,570,279.00	2,276,247.00	15,525,965.00
	70	2,5,6	5,498,597.00	8,967,764.00	2,410,322.00	16,876,683.00
	80	1,2,4	2,576,097.00	13,803,996.00	2,276,247.00	18,656,340.00

	90	4,5,6	421,901.00	18,822,058.00	2,364,081.00	21,608,040.00
	100	2,4,5	0.00	19,685,809.00	2,173,433.00	21,859,242.00
4	0	2,3,4,5	8,206,533.00	3,092,925.00	3,153,025.00	14,452,483.00
	10	2,3,4,5	8,206,533.00	3,092,925.00	3,153,025.00	14,452,483.00
	20	2,3,4,5	8,206,533.00	3,092,925.00	3,153,025.00	14,452,483.00
	30	2,3,4,5	8,206,533.00	3,092,925.00	3,153,025.00	14,452,483.00
	40	1,2,4,5	7,315,884.00	4,103,221.00	3,049,365.00	14,468,470.00
	50	1,2,4,5	7,316,655.00	4,103,221.00	3,049,365.00	14,469,241.00
	60	1,2,4,5	7,592,102.00	4,154,042.00	3,049,365.00	14,795,509.00
	70	1,2,4,5	6,089,704.00	7,316,411.00	3,049,365.00	16,455,480.00
	80	1,2,4,6	3,660,557.00	11,075,943.00	3,190,173.00	17,926,673.00
	90	1,4,5,6	1,452,316.00	16,957,756.00	3,240,013.00	21,650,085.00
	100	1,2,4,5	0.00	19,685,809.00	3,049,365.00	22,735,174.00
5	0	1,2,4,5,6	9,001,207.00	2,252,614.00	3,963,291.00	15,217,112.00
	10	1,2,4,5,6	9,001,207.00	2,252,614.00	3,963,291.00	15,217,112.00
	20	1,2,4,5,6	9,001,207.00	2,252,614.00	3,963,291.00	15,217,112.00
	30	1,2,4,5,6	9,001,207.00	2,252,614.00	3,963,291.00	15,217,112.00
	40	1,2,4,5,6	8,663,665.00	2,612,921.00	3,963,291.00	15,239,877.00
	50	1,2,3,4,5	9,854,431.00	1,364,001.00	4,028,957.00	15,247,389.00
	60	1,2,4,5,6	7,979,223.00	3,453,753.00	3,963,291.00	15,396,267.00
	70	1,2,4,5,6	8,649,880.00	3,562,994.00	3,963,291.00	16,176,165.00
	80	1,2,4,5,6	4,903,290.00	8,321,948.00	3,963,291.00	17,188,529.00
	90	1,2,4,5,6	2,487,228.00	15,129,949.00	3,963,291.00	21,580,468.00
	100	1,2,4,5,6	0.00	19,685,809.00	3,963,291.00	23,649,100.00
6	0	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	10	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	20	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	30	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	40	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	50	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	60	1,2,3,4,5,6	9,853,661.00	1,364,001.00	4,942,883.00	16,160,545.00
	70	1,2,3,4,5,6	9,873,564.00	1,364,001.00	4,942,883.00	16,180,448.00
	80	1,2,3,4,5,6	5,924,171.00	5,998,786.00	4,942,883.00	16,865,840.00
	90	1,2,3,4,5,6	3,758,304.00	12,986,117.00	4,942,883.00	21,687,304.00
	100	1,2,3,4,5,6	0.00	19,685,809.00	4,942,883.00	24,628,692.00

Table A-2: Sensitivity analysis of 18-node network according to parameter β

No. of hubs	Beta	Locations	Collaborative Costs	Non-collaborative Costs	Costs of establishing the transfer facilities	Total Costs
7	0.0	1,2,6,8,13, 16,18	17,597,703.00	17,344,362.00	6,413,510.00	41,355,575.00
	0.1	1,2,6,8,13, 16,18	17,597,703.00	17,344,362.00	6,413,510.00	41,355,575.00
	0.2	1,2,6,8,13, 16,18	17,359,886.00	17,616,303.00	6,413,510.00	41,389,699.00
	0.3	1,2,6,8,13, 16,18	16,053,373.00	19,440,844.00	6,413,510.00	41,907,727.00
	0.4	1,2,6,8,13, 16,18	16,053,373.00	19,440,844.00	6,413,510.00	41,907,727.00
	0.5	2,4,5,7,9, 13,17	16,916,298.00	18,893,950.00	6,475,251.00	42,285,499.00
	0.6	1,2,6,7,8, 13,17	14,779,719.00	23,271,712.00	6,499,255.00	44,550,686.00
	0.7	1,2,6,9,12, 13,17	12,679,291.00	29,029,782.00	6,213,862.00	47,922,935.00
	0.8	1,2,4,5,6, 8,13,14	7,545,752.00	37,922,079.00	6,380,419.00	51,848,250.00
	0.9	1,2,3,4,5, 6,13	5,645,408.00	44,205,322.00	6,558,424.00	56,409,154.00
	1.0	1,9,11,12, 14,15,18	0.00	54,714,761.00	5,700,654.00	60,415,415.00
8	0.0	1,2,6,8,11, 13,16,18	17,993,130.00	16,069,206.00	7,203,737.00	41,266,073.00
	0.1	1,2,6,8,11, 13,16,18	17,993,130.00	16,069,206.00	7,203,737.00	41,266,073.00
	0.2	1,2,6,8,11, 13,16,18	17,755,311.00	16,341,147.00	7,203,737.00	41,300,195.00
	0.3	1,2,6,8,11, 13,16,18	16,448,798.00	18,165,688.00	7,203,737.00	41,818,223.00
	0.4	1,2,6,8,11, 13,16,18	16,448,798.00	18,165,688.00	7,203,737.00	41,818,223.00
	0.5	2,4,5,7,9, 11,13,17	17,311,723.00	17,618,794.00	7,265,478.00	42,195,995.00
	0.6	1,2,3,6,7, 8,13,17	17,182,893.00	19,625,642.00	7,472,744.00	44,281,279.00

	0.7	1,2,6,9,12, 13,17,18	14,203,600.00	25,836,082.00	7,062,350.00	47,102,032.00
	0.8	1,2,3,4,5, 6,16,17	8,050,944.00	35,719,616.00	7,527,850.00	51,298,410.00
	0.9	1,2,3,4,5, 6,9,13	6,123,102.00	43,460,234.00	7,326,079.00	56,909,415.00
	1.0	1,9,10,11, 12,14,15,18	0.00	54,714,761.00	6,601,611.00	61,316,372.00
9	0.0	1,2,6,8,11, 13,14,16,18	18,361,042.00	15,626,878.00	7,999,221.00	41,987,141.00
	0.1	1,2,6,8,11, 13,14,16,18	18,361,042.00	15,626,878.00	7,999,221.00	41,987,141.00
	0.2	1,2,6,7,9,11, 13,16,18	17,755,311.00	16,341,147.00	7,952,022.00	42,048,480.00
	0.3	1,2,3,6,7,9, 12,14,17	17,993,130.00	16,069,206.00	8,012,584.00	42,074,920.00
	0.4	1,2,3,6,7,9, 12,14,17	17,993,130.00	16,069,206.00	8,012,584.00	42,074,920.00
	0.5	1,2,3,6,7,9, 11,13,17	18,014,901.00	16,069,206.00	8,064,791.00	42,148,898.00
	0.6	1,2,3,6,7,8, 12,13,17	17,435,659.00	18,350,486.00	8,331,996.00	44,118,141.00
	0.7	1,2,5,6,9,12, 13,17,18	15,611,231.00	23,260,345.00	8,005,004.00	46,876,580.00
	0.8	1,2,3,4,5, 6,7,8,9	8,763,847.00	34,158,053.00	8,321,663.00	51,243,563.00
	0.9	1,2,3,4,5,6, 13,16,17	7,424,302.00	41,026,551.00	8,444,566.00	56,895,419.00
	1.0	1,9,19,11,12, 13,14,15,18	0.00	54,714,761.00	7,518,327.00	62,233,088.00

VITA

Jiri Tylich was born in Hranice, Czech Republic on September 1, 1986, and the second born and son of Zdenka and Jiri Tylich. After graduating from Gymnazium Hranice in Hranice, Czech Republic, he entered Czech Technical University in Prague, Faculty of Transportation Sciences, in 2006. He received his Bachelor degree in Technology in Transportation and Telecommunications – Transportation Systems and Technology at Czech Technical University in Prague, Faculty of Transportation Sciences, in June 2010. In October 2010, He joined the Transatlantic Full-time Dual Master's Program in the Transportation and Logistic Systems which was jointly offered by the Czech Technical University in Prague, the Faculty of Transportation Sciences, and The University of Texas at El Paso.

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