DEVELOPMENT OF A STRATEGIC FREIGHT NETWORK OPTIMIZATION MODEL

Luís Couto Maia
António Fidalgo do Couto
Universidade do Porto
Faculdade de Engenharia
Portugal

RESUMO
Neste artigo é apresentada uma estrutura para o desenvolvimento e potencial aplicação de um modelo estratégico de transporte de mercadorias, para optimização de redes de transporte. A estrutura está dividida em três blocos: desenvolvimento de um modelo estratégico de transporte de mercadorias (modelo de afectação de tráfego); desenvolvimento de um modelo estratégico de optimização de redes; aplicações potenciais do modelo desenvolvido em redes artificiais. O modelo de optimização considerará diferentes factores, especificamente custos de transporte, robustez da rede e impactes ambientais, sendo que será suficientemente flexível para se adaptar a possíveis mudanças em factores chave. Isto permitirá que seja usado numa grande diversidade de cenários, incluindo a sua potencial aplicação em várias redes artificiais sob condições diferentes. Com isto será possível analisar a relação entre mudanças em factores importantes, tais como o preço do petróleo, e o seu impacto no tipo de melhorias necessárias na rede de transportes.

ABSTRACT
In this paper, a framework for the development and potential application of a strategic freight transportation network optimization model is presented. The framework is divided in three blocks: development of a strategic freight transportation model (traffic assignment model); development of a strategic network optimization model (built on top of the freight transportation model); potential application of the developed model on artificial networks. The optimization model will consider different factors, namely transportation costs, network robustness and environmental impacts, being that it will be flexible enough to accommodate for possible changes in key factors. This will allow it be used on a wide range of scenarios, including being potentially applied to several different artificial networks under different conditions. Based on that, it will be possible to analyze the relation between variations on major factors such as the price of oil and their impact on the type of transportation network improvements needed.

1. INTRODUCTION

Although freight transportation plays a crucial role in the day to day life of any modern society, being critical to a large part of the economy, it is a subject that has received much less attention by the academia than its passenger counterpart. This is likely due to the fact that it is a subject not as appealing to policy makers and the general public as passenger transportation. Adding to the natural complexity of this subject (due to the multiplicity of goods transported, the existence of a significant share of empty trips, and many other factors), there is still the difficulty in getting the needed data, due to the general lack of complete and up to date databases, and the unwillingness of transportation companies to share data due to confidentiality reasons. Even so, a considerable amount of research has already been done in the past, and, in recent years, more and more attention is being given to this subject. An analysis of the papers that have been written in this field of study leads to the conclusion that there is a considerable diversity of models, being that each paper tends to focus only on a part of the freight modeling process.

The great economic importance that freight transportation has in today’s modern societies makes it ever more important to think of it as a separate part of the transportation spectrum (instead of being grouped with passenger transportation, as it frequently happens), planning the future of transportation networks with freight transportation in mind. The impact on freight transportation of investments in transportation infrastructures should be analyzed independently from passenger studies, or side by side with them. This is justified not only by the importance of freight in itself, but also because the needs of freight transportation are different from those of passenger transportation, which means that the network investments needed to improve freight transportation can be considerably different from those aimed at improving passenger transportation. In order to assess the quality of different network improvement solutions, it is necessary to define the parameters which will be used to measure the value of each of the scenarios analyzed. This is a problem that doesn't have only one possible solution, being that various different parameters can be used.

Strategic analysis and planning of investments on transportation infrastructure is something that inherently has a long term horizon and, as such, has to be carefully thought through. The long term nature of this kind of analysis means that some factors and parameters that today assume a certain value, may change quite significantly in the long run, due to different factors such as the rising price of oil or the ever increasing environmental conscience of society. As such, it is important to take that into account and assume that there may be fundamental changes in some key factors, such as, for example, the price of oil. This means that apart from equating many possible scenarios for the future, the impact of these network improvements has to be tested with different values for key parameters such as the price of oil (which has a considerable impact on transportation costs). This possible variation of key factors means that the same network investment can have very different impacts on the transportation of freight depending on some exogenous factors that are volatile and not controlled by planners. Due to that, the best possible investment scenario will likely vary according to the values of the parameters used, meaning that, in the end, the most responsible investments are those that deliver a good solution when key parameters assume various possible values, and not necessarily the one that is best in a specific situation.

The goal of this paper is to describe a proposed strategic freight transportation network optimization model that weights in several different factors and is flexible enough to accommodate for possible changes in key factors, so that it can be used as an important tool in planning investments for new and improved transportation infrastructures.

In the proposed framework, the first block is devoted to the development of a strategic freight transportation model (traffic assignment model), the second block is dedicated to the development of a strategic network optimization model and the third block is dedicated to the potential application of the developed model on artificial networks. This paper is organized following the structure of the framework presented in figure 1.

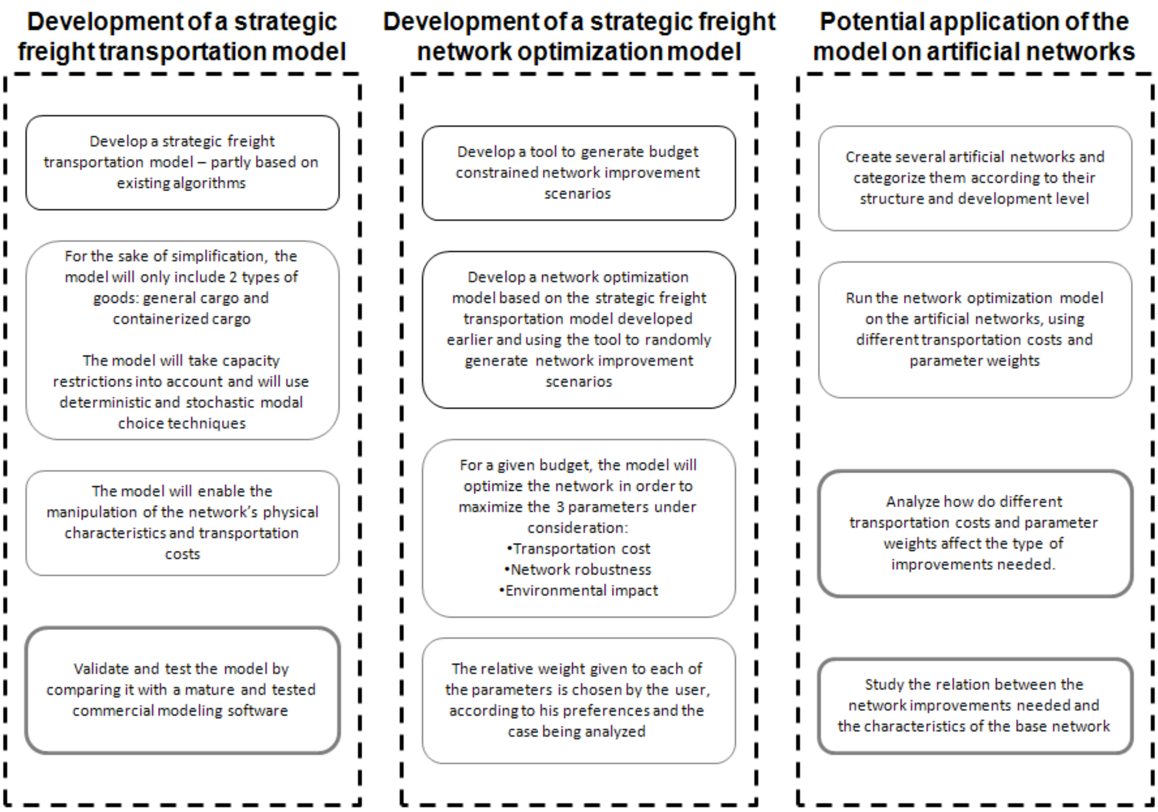

Figure 1: Structure of the proposed framework

2. BACKGROUND

2.1. Freight transportation modeling

2.1.1. Costs modeling

In a freight transportation model, the transportation costs are associated with the use of each link. To begin with, all transportation costs are generally estimated in a generic unit, usually the cost per ton per kilometer. This way costs can be generalized for each link category and applied to all the different links, regardless of the amount of freight being transported through it (as long as no congestion effect is considered) or the length of the link. These costs are usually not defined solely by the economic costs, also considering time costs and possibly other types of costs. This definition of cost based on various factors that are deemed to have an impact on the decision of freight transporters is what is usually referred to as generalized costs. The generalization that has to be made in order to obtain a cost per ton per km for each category of link is a delicate process, where many choices have to be made. This is especially true in the case of large, broad scoped aggregated models, where, as the scale is quite big, and as the level of aggregation is consequently also quite high, the generalization is hard to be made, because each type of link category encompasses a significant variety of possible realities, not being very specific.

In reality, there are many different factors that affect the cost of transporting a ton of freight for one kilometer of road or rail, namely the capacity of the vehicles circulating in the link, their loading factor, etc. Although a link category should limit those possibilities, by defining the type of vehicles that may circulate on each link category, there is always a possible margin, which can be considerable. In the case of rail transportation, the length of freight trains can vary considerably, even within the same category of lines, with the length (and hence, the cargo capacity) of a freight train having a very significant impact on the cost per ton, being lower for longer trains (Janic, 2008). There are other important factors which can also vary considerably, namely the frequency of service and the distance traveled. Still, it is very hard to model the impact of frequency and distance travelled in a strategic (therefore aggregated) transportation model, which means that modelers have to have a good knowledge of the reality, in order to include the average impact of these factors in the average costs.

The time cost, which represents the time it takes to move one person or an amount of goods from one place to another, is also a very important decision making variable. In terms of freight transportation, the impact that the time of travel has on the decision process varies considerably for different types of freight, being crucial for the movement of some high valuable freight, but not very important for other goods. In any case, the quantification and explicit modeling of the cost of time is a indispensable part of any transportation model, being that one of the most widely used method to quantify the value of freight transportation time is the use of stated preference or revealed preference studies, that measure the shippers' perception of the value of time (Bolis and Maggi, 2003; Kang *et al.*, 2010). Although the quantification of the value of time is, by nature, not a very objective matter, all transportation modeling studies have to consider some value, being easy to find in the literature a great variety of cases with different values.

2.1.2. Modal choice

Generally, freight transportation models use the total generalized costs of each alternative mode to perform the mode choice, simply by choosing the mode with the smaller costs. The problem with this general approach is that, as most models are strategic models, with high levels of aggregation, many factors that have a decisive influence on the modal choice are often disregarded. While there is no doubt that the generalized cost is a major deciding factor in the freight transportation modal choice, many other factors such as the shipment size and the service quality are also very important (Zlatoper and Austrian, 1990; Andersen and Christiansen, 2009). Although the explicit modelation of those factors in the context of a strategic model is not feasible, it is possible to adopt a stochastic approach for the modal choice process, where shippers don't limit themselves to choosing the mode of transport with least cost. This approach has the merit of assuming shippers do not just choose the transportation mode based on the total generalized cost, assuming that there are other important factors that introduce some unpredictability in the decisions. The most commonly used function to deal with stochastic modal choice is the Logit function, which, due to its versatility and convenience has been used extensively in the literature (Tsamboulas and Moraitis, 2007; Oum, 1979; Jourquin, 2005).

2.1.3. Freight transportation models and assignment techniques

In order to build and run a freight transportation model, the previous described topics have to be interlinked to form a transportation model, where, given a demand O/D matrix, the freight traffic is distributed throughout the network, using traffic assignment techniques. The different assignment techniques that can be used in a transportation model can be divided in four classes, as seen in table 1.

Table 1: Assignment techniques (Jourquin, 2005)

	Variable perception of the costs	
Capacity constraint	No	Yes
No	All or Nothing	Stochastic (multi-flow)
Yes	Equilibrium	Stochastic equilibrium

As it is described in the table, there are two big decisions that have to be made before choosing a model: if there are going to be capacity constraints and if the perception of costs is variable. Capacity constraint models are those in which the capacity of links is limited, imposing a limit on the amount of traffic that can use each link, and often also including time penalties due to congestion when certain limits of traffic are exceeded. As for the perception of costs being variable or not, that reflects whether or not the transportation mode and route decisions are made uniquely based on the lowest generalized cost (no variable perception), or if some stochasticity is included (using methods such as the Logit function), spreading the traffic through different modes and routes. Combing these two choices, four possible assignment techniques are possible. From those four described assignment techniques, three of them are frequently used in the literature, namely all or nothing assignments (Jourquin and Beuthe, 1996; Beuthe *et al.*, 2001), equilibrium assignments (Crainic *et al.*, 1990; Jourquin and Limbourg, 2006) and stochastic (multi-flow) assignments (Jourquin, 2005). The exception is stochastic equilibrium models, which are rarely used due to their inherent complexity.

2.2. Network optimization modeling

2.2.1. Generation of network improvement scenarios

The first thing that has to be done in order to build a transportation network optimization model is to create of a tool that generates network improvement scenarios. A network improvement operation is an investment in the transportation infrastructure that improves the quality of a given link. It may represent an upgrade in the quality of the link, or the construction of a new link from scratch, being that in order to quantify the improvements, the network may be divided into several possible link levels, in which level zero corresponds to just the possibility of building a new link (Santos *et al.*, 2008). All this network improvement operations must have an associated cost, in order to quantify the money spent in a given network improvement scenario. Having well defined network conditions as well as construction and upgrading costs are the basic foundations needed for the development of a network improvements generator tool, capable of creating improvement scenarios according to a defined budget limit. Given that, what a network improvements generator does is to create multiple network improvement scenarios that respect a certain budget limit.

2.2.2. Optimization of network improvements

The aim of an optimization process is to find out how the transportation network should be improved, in order to maximize the appropriate indicators, defined by the planner. The optimization parameters that are defined by each planner for each case can vary considerable, with each of those parameters having to have an associated quantitative indicator, in order for them to be objectively analyzed. Many different parameters can be used in order to assess the quality of transportation solutions, namely the total generalized cost, the robustness of the network, the environmental impact caused and the equity of the territorial accessibility

(Santos *et al.*, 2009). There are many possible ways to quantify those parameters, from very complex methods to relatively simple ones, being that the robustness of the network can simply be quantified as the existent spare capacity of the network, the environmental impact can be measured using an estimation of the carbon dioxide emissions and the equity of the territorial distribution can be assessed using the Gini coefficient.

Most of the research found in the literature on the subject of network optimization was performed using two models: the discrete network design problem (DNDP) model and the continuous network design problem (CNDP). The former concentrates on the addition of new links, while the latter focus on the (continuous) improvement of existing links. It is also possible to use an approach based on a mix of both models, with discrete improvements on existing or possible links (Santos *et al.*, 2010). Although the research in the area of transportation network optimization that is found in the literature focus almost exclusively on passenger transportation, the same optimization process can be applied to freight transportation.

Due to the considerable complexity of the transportation networks and to the discrete nature of some models, there is no practical analytical solution for this problem, which leads to the adoption of heuristic techniques. Several techniques have been successfully used to address this kind of problems, predominantly metaheuristics such as tabu search, simulated annealing and genetic algorithms (Crainic, 2000). A recent paper on this subject tested three different algorithms to address the problem: an add plus interchange algorithm, a variable neighborhood search algorithm and an enhanced genetic algorithm (Santos *et al.*, 2009). The authors concluded that the enhanced genetic algorithm was the one who gave best solutions, which shows that genetic algorithms are a suitable heuristic to deal with this type of problems.

3. DEVELOPMENT OF A FREIGHT TRANSPORTATION MODEL

3.1. Network structure

The proposed freight transportation model is going to be designed to model macro networks with a high aggregation level, namely national or international networks, being a strategic planning model (Crainic and Laporte, 1997). It will include the possibility of defining a capacity limit for links and transfers, in order to reflect the fact that some trunk inter-city routes often work at their capacity limit and are unable to accommodate more traffic, particularly major rail lines. It is important to notice that, as only freight transportation is being considered in this model, the capacity of the links represents the capacity that is left by passenger traffic. This capacity will be defined as a maximum vehicles flow, being that for each link and cargo type there will be an associated capacity per vehicle, so that freight flows can be converted in vehicle flows. However, the model will not give the users the possibility to include congestion effects, imposing fixed costs in all kind of links, which is justified by the fact that it is much simpler to solve it if there are no variable costs. Also as this is a strategic model, it makes sense not to include congestion, since inter-city freight movements are generally not significantly affected by congestion delays, which makes equilibrium models (which tale congestion into account) not well suited for inter-city models (Jourquin, 2005).

3.2. Freight product types and costs structure

The freight model will consider two different types of goods: general cargo, and intermodal cargo. The reason behind this partition of cargo in those two categories is the fact that intermodal cargo, usually transported in containers, is the only type of cargo that is frequently transported by more than one mode in the same trip, therefore being the only one that uses intermodal terminals. As for the rest of the cargo (general cargo), it is usually transported by the same mode of transport along an entire trip, with the possible exception of the last mile connectors. This division of product types makes it possible to adopt different modeling approaches for each one of them, being that general cargo will not use intermodal terminals, having to choose a specific transportation mode for each trip. As for intermodal cargo, it can use the intermodal terminals, allowing the use of different transportation modes in the same trip. This approach, in which only intermodal container cargo is allowed to use intermodal terminals is not new, having already been employed in other studies (Beuthe *et al.*, 2001).

The structure of costs that will be used in the model will be freely defined by the users, as long as it respects the fixed cost principle that was referred to before, which means that the cost per ton of using a link will not be dependent on the amount of traffic using it. The total transportation cost generated by a link will be directly proportional to the flow of freight that uses it, generally being divided in an economic cost and a time cost. The time cost will be converted to generalized costs through the use of a value of time variable, whose value will be defined by the user. The model will give its users the liberty to include all different kinds of costs they deem appropriate, as long as they are all converted to generalized costs. As the two different types of cargo will have so diverse characteristics, they will also have different cost functions, enabling the model to be more flexible, as it allows users to use different measure units for general cargo and intermodal cargo. This can be a useful feature, as general cargo is usually defined in tones, while intermodal transportation is more frequently quantified in terms of twenty foot equivalent units (TEU’s), which is the usual measure unit used for containerized cargo.

3.3. Assignment algorithm and validation

The assignment technique that will be used can be classified as a type of stochastic equilibrium, due to the fact that it takes capacity constraints into account, and that a variable perception of costs is used in the case of general cargo. Still, as no congestion effects are considered, this will be a stochastic equilibrium model that is rather simplified, which makes it less complex and therefore capable of being solved without significant problems. In order for the capacity limits to be taken into account, an incremental method is going to be used, with only a part of the total traffic from each of the different cargo categories being loaded into the network at each interaction. After each iteration, all of those links whose capacity has been exceeded will be excluded, being removed from the network in further interactions. This is a simple and effective method that is well suited to deal with the problem of capacity limits. At each iteration, two different processes will be used, one for each of the different cargo categories. Still, in both cases, the same least cost path algorithm will be used to calculate the cheapest route between each O/D pair. The difference will be that in the case of intermodal cargo, all the traffic from each O/D pair will follow the least cost route, without any restriction on the type of links or modes used, meaning that different modes can be used in the same trip. As for general cargo, the assignment method will compute the least cost route for each transportation mode available. Based on the costs offered by each mode, the traffic will be split between those transportation modes using a Logit function. In case there is only one transportation mode available between a given O/D pair, all the traffic will use the least cost route offered by that mode.

Finally, the proposed model will be tested against a commercial freight transportation modeling software, by performing various tests on small artificial networks, in which various effects can tested, and comparing the results obtained when using both models. This will be done in order to validate the model and ensure that it offers a solid modeling solution.

4. DEVELOPMENT OF A NETWORK OPTIMIZATION MODEL

4.1. Development of a tool to generate network improvement scenarios

The first step in the development of a model to generate network improvement scenarios is to define the structure of the base network and the improvement possibilities. In the proposed approach, a network structure where the links have clearly defined and discrete quality levels will be used. Each quality level corresponds to a different link type, which can vary from the level zero, where there is only the possibility of a link being built, to the highest level, which corresponds to the best possible quality link. For each transportation mode, the defined link quality levels will be associated with specific link characteristics. In the proposed model there will be two different transportation modes (road and rail) and the characteristics that will vary according to the link quality level will be different for each mode. In the case of roads, the attributes that will change according to the level of the links will the capacity, the average speed and the cost per km. As for the rail links, the varying attributes will be capacity, average speed and the average capacity per vehicle. The average capacity per vehicle (per train convoy, in the case of rail) has a significant impact on costs, reflecting the fact that different rail lines allow for diverse maximum train lengths, which is reproduced in the maximum amount of freight each train convoy carries. Apart from the definition of all possible improvements to the transportation network, it is necessary to quantify the cost of those improvements, which can be estimated based on consultation of the existing literature (Affuso *et al.*, 2000) and on the collection of data on recent transportation infrastructure works. After having all the network improvement parameters and possibilities well defined, it is relatively easy to develop an algorithm that randomly generates network improvements, subject to a certain budget. A local search heuristic can be used to improve the randomly created solutions, in order to take full advantage of the budget available, by maximizing the percentage of the available budget that is effectively used.

4.2. Parameters used to evaluate the solutions

The factors that will be considered for the assessment of the quality of the network improvement solutions will be the total cost, the robustness of the network and its environmental impact. The total cost will be quantified by the total generalized cost produced by the solution. This reflects the costs that are supported by the freight carriers, and according to which they make their transportation decisions. As for the parameter dedicated to the robustness of the network, it will quantify the reserve capacity of the network, which is an indicator of the capacity of the network to accommodate unexpected increases in traffic demand. Regarding the parameter dedicated to the environmental impact, it will be quantified by the carbon dioxide emitted by all the vehicles transporting freight. This will be estimated by admitting that a ton*km of freight will produce a certain amount of carbon dioxide, according to the transport mode and quality of the link on which it travels.

4.3. Network optimization model

The proposed network optimization model can be divided in several steps, being that the general structure of the optimization process can be seen in figure 2.

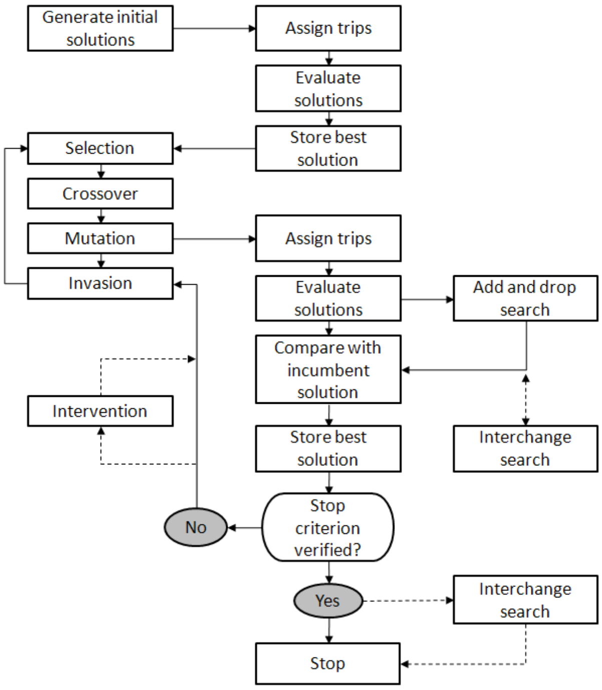

Figure 2: Schematic representation of the proposed approach and algorithm (Santos *et al.*, 2009) - adapted

Except for small-size instances, this network optimization process is extremely difficult to be solved to exact optimality analytically, which is why it will be handled using an heuristic. The proposed approach is based on an enhanced genetic algorithm that was developed to solve a road network improvement model (Santos *et al.*, 2009) and that goes beyond traditional algorithms in several aspects. It presents good results when dealing with large transportation networks, with reasonable processing times, being well suited to deal with the optimization problem proposed in this work.

5. POTENTIAL APPLICATION OF THE MODEL ON ARTIFICIAL NETWORKS

The freight network optimization model can potentially be applied to artificial networks in order to study the effects of changes in costs and other parameters on the type of network improvements that should be done.

5.1. Generation of artificial networks

In order to create a sample of artificial networks which encompasses different possible network configurations, several different networks will have to be generated. The artificial networks will have to guarantee a representative diversity of possible network configurations, and therefore some basic network categories will have to be defined, as a function of the network structure and development level, following a certain classification method. The network structure may be more mononuclear, concentrated around a few big poles, or more polynuclear, being more evenly distributed between various poles. As for the development level, it may be less developed, with lesser quality links, and poorer generational poles or more developed. The development of artificial networks with different structures and development levels aims at reflecting the diversity of transportation networks that exist in real world, with the creation of various artificial networks for each defined category.

Apart from the creation of the artificial networks, it is also necessary to estimate the demand for freight on each of those networks. As there is only some artificially created basic information about the economic importance of the generating poles, the essential aspect is to ensure that the freight production and attraction quantities for each pole are realistic. That can be assured by correlating the size of the generating poles with the amount of freight they produce and attract, based on available statistical data. As for the distribution step, that can be addressed by using a relatively simple gravity model based on the size and distance between the poles.

5.2. Application of the model considering variable cost factors and parameter weights

Apart from the creation of a wide range of different networks, a number of different cost scenarios, where the cost factors will vary, will also be considered. The main goal of the creation of more than one cost scenario is to study the impact of important changes in the transportation costs, which could be caused by events such as a sharp increase in the price of oil, which has a major impact on the costs of transportation. By doing so, it will be possible to understand what would be the impact of important changes in transportation cost variables on the planning of network improvements. The weights given to each of the three parameters that are used to evaluate each network improvement solution may also be changed, in order to simulate a greater concern for factors such as the environmental impact.

5.3. Expected results

With each artificial network being optimized for different cost scenarios and parameter weights, it will be possible to study the impact that the variation of those factors has on the type of network optimizations needed. The goal of this analysis is to establish the relation between the variation of each factor and its impact on the network improvements needed, by understanding for instance the impact that a sharp increase in the price of oil would have on the type of infrastructure investments that should be made. As for the division by categories of the artificial networks, its purpose is to understand if there is a general pattern in the type of network improvements needed for each category of artificial network. If the results obtained in this type of analysis are clear and consistent, it will be possible to draw some general conclusions on how to optimize transportation networks in order to improve freight transportation for each network category.

6. CONCLUSIONS

In this paper, a work proposal for the development and application of a freight transportation network optimization model is presented. For a given investment budget, the proposed model will be capable of optimizing the network improvements that should be done in order to minimize the total transportation costs and the environmental impact and maximize the network robustness. This model can potentially be applied to several artificial networks in an effort to understand if there is a pattern in the way transportation investments should be made and to study what would be the impact of major changes in important factors, such as a sharp rise in the price of oil, on the type of network improvements that should be done.

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Luís Couto Maia (luis.maia@fe.up.pt)
António Fidalgo do Couto (fcouto@fe.up.pt)
Departamento de Engenharia Civil, Faculdade de Engenharia da Universidade do Porto
Rua Dr. Roberto Frias, s/n 4200-465 Porto Portugal