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Contributions for network design in urban freight distribution systems

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Submitted to the Faculty of Engineering of the University of Porto, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Engineering and Industrial Management, supervised by Jorge Manuel Pinho de Sousa, Full Professor of the Faculty of Engineering of the University of Porto, and by Bruno de Athayde Prata, Assistant Professor of the Federal University of Ceará.

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“What we know is a drop, what we do not know is an ocean.”

Isaac Newton

Abstract

Central areas of large cities offer in general many advantages to their inhabitants. Typically, a large number of products, services, and opportunities are available in those urban zones, thus increasing life quality. Unfortunately, these benefits are associated with increasing transportation activities, that can cause serious problems to people city routines, such as traffic congestion, excessive energy consumption, and pollution (noise and air).

In this context, city logistics is, in fact, the most relevant factor in many economic and social activities for both inhabitants and companies of many cities. It is, therefore, more and more important to fully understand and study the interactions between stakeholders (from suppliers to consumers) and their motivations, and how to get insights on how to improve urban freight.

The approach developed in this thesis is in line with these concerns and proposes a new transport system that consists of transporting freight in long-haul passenger vehicles (buses). We believe this approach will contribute to increasing transport efficiency, reducing costs, while decreasing the environmental and social impacts resulting from transport traffic, in particular in what concerns the reduction of vehicles circulation around and between cities.

For supporting the design, assessment, and deployment of this approach, a mixed-integer mathematical programming model was developed and implemented. This approach aims at minimizing transport costs and times related to urban freight flows, by taking advantage of the passenger transport network. In this model, two objectives were considered reflecting the concerns and perspectives of the different system stakeholders.

The problem under study was viewed as a multi-commodity network flow problem with time windows, multi transport-lines, and multiple vehicles. Two heuristic approaches based on mathematical programming were designed to solve it: Size Reduction, and LP-and-fix. Some instances for this new variant of the multi-commodity network flow problem were generated to test the efficiency of the algorithms.

Finally, the approach developed in this thesis was validated and assessed by solving a case study designed around a real-world problem (the case of the intercity passenger transport system, in Ceará, Brazil).

Keywords: City logistics; urban freight; multi-commodity network design problem; distribution system; mixed integer linear programming; decision support systems.

Resumo

As áreas centrais das grandes cidades oferecem em geral muitas vantagens para os seus habitantes. Normalmente, um grande número de produtos, serviços e oportunidades estão disponíveis nessas zonas urbanas, aumentando assim a qualidade de vida da população. Infelizmente, esses benefícios estão associados ao aumento das atividades de transporte que podem causar sérios problemas às rotinas da cidade, como congestionamento de tráfego, consumo excessivo de energia e poluição (ruído e ar).

Neste contexto, a logística urbana é, de fato, o fator mais relevante em muitas atividades econômicas e sociais para os habitantes e empresas de muitas cidades. É, portanto, cada vez mais importante entender e estudar completamente as interações entre as partes interessadas (de fornecedores a consumidores) e suas motivações, e obter *insights* sobre como melhorar o transporte urbano de cargas.

A abordagem desenvolvida neste trabalho está alinhada com essas preocupações e apresenta um novo sistema de transporte que consiste no transporte de cargas em veículos de passageiros de longa distância (ônibus). Acreditamos que essa abordagem contribuirá para aumentar a eficiência do transporte, reduzindo custos e diminuindo os impactos ambientais e sociais resultantes do tráfego de transportes. Isso resultará especialmente na redução de veículos circulando entre as cidades.

Para apoiar o projeto, a avaliação e a implementação dessa abordagem, um modelo de programação matemática inteira-mista foi desenvolvido. Esta abordagem visa minimizar os custos e tempos de transporte relacionados aos fluxos de carga urbana, utilizando a rede de transporte de passageiros. Nesse modelo, dois objetivos foram considerados refletindo as preocupações e perspectivas dos diferentes *stakeholders* do sistema.

O problema em estudo foi o *multi-commodity network flow problem, with multi-transport lines, multiple vehicles and time windows*. Duas abordagens heurísticas baseadas em programação matemática foram realizadas para resolvê-lo: *size reduction* e *LP e Fix*. Alguns exemplos dessa nova variante do problema de fluxo em rede de mercadorias múltiplas foram gerados para testar a eficiência dos algoritmos.

Por fim, a abordagem desenvolvida neste trabalho foi validada resolvendo um problema do mundo real, avaliado em um estudo de caso (o caso do sistema intermunicipal de transporte de passageiros, no Ceará, Brasil).

Palavras-chave: Logística urbana; transporte urbano de carga; problema de fluxo em rede para múltiplas mercadorias; sistema de distribuição; programação linear inteira-mista; Sistemas de Apoio à Decisão.

Resumé

Les zones centrales des grandes villes offrent en général de nombreux avantages à leurs habitants. Généralement, un grand nombre de produits, services et opportunités sont disponibles dans ces zones urbaines, améliorant ainsi la qualité de vie. Malheureusement, ces avantages sont associés à une augmentation des activités de transport qui peuvent causer de graves problèmes aux habitants, comme la congestion routière, la consommation excessive d'énergie et la pollution (bruit et air).

Dans ce contexte, la logistique urbaine est en réalité le facteur le plus pertinent dans de nombreuses activités économiques et sociales, tant pour les habitants que pour les entreprises de nombreuses villes. Il est donc de plus en plus important de bien comprendre et d'étudier les interactions entre les parties prenantes (des fournisseurs aux consommateurs), leurs motivations et la manière d'obtenir des informations sur la manière d'améliorer le fret urbain.

L'approche développée dans ce travail répond à ces préoccupations et présente un nouveau système de transport consistant à transporter des marchandises dans des véhicules de transport longue distance (autobus). Nous pensons que cette approche contribuera à accroître l'efficacité des transports, à réduire les coûts et à réduire les impacts environnementaux et sociaux du trafic de transport. Cela résultera notamment de la réduction de la circulation des véhicules autour et entre les villes.

Pour la conception, l'évaluation et la mise en œuvre de cette approche, un modèle de programmation mathématique à nombres entiers mixtes a été conçu. Cette approche vise à minimiser les coûts et les temps de transport liés aux flux de fret urbains en tirant parti du réseau de transport de passagers. Dans ce modèle, deux objectifs reflétant les préoccupations et les perspectives des différents acteurs du système ont été pris en compte.

Le problème à l'étude a été mis au point en tant que problème de flux de réseau multi-produits avec fenêtres temporelles, lignes de transport multiples et véhicules multiples. Deux approches heuristiques basées sur la programmation mathématique ont été entreprises pour le résoudre: Réduction de taille et LP et Fix. Certaines instances de cette nouvelle variante du problème de flux de réseau multi-produits ont été générées pour tester l'efficacité des algorithmes.

Enfin, l'approche développée dans ce travail a été validée pour résoudre un problème réel, puis évaluée dans une étude de cas réelle (le cas du système de transport de passagers interurbain à Ceará, au Brésil).

Mots-clés: logistique de la ville; fret urbain; problème de conception de réseau multi-produits; système de distribution; programmation linéaire en nombres entiers mixtes; systèmes d'aide à la décision.

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Chapter 1

Introduction

Summary: The main goal of this chapter is to present a general view of this doctoral thesis that aims at developing a new approach to integrate the intercity passenger transport and the urban freight, and at solving the problem using heuristic techniques. The first section presents the motivation for this research and the problem definition. The second section presents the thesis objectives and research questions, while in the third section a thesis overview is presented.

1.1. Motivation and problem definition

Central areas of large cities offer in general many advantages to their inhabitants. Typically, a large number of products, services, and opportunities are available in those urban zones, thus increasing life quality levels. Unfortunately, these benefits are in general strongly associated with higher traffic congestion and pollution, which are mainly due to increasing transportation activities. These activities are obviously required to guarantee the material flows needed to supply cities, but they can cause serious problems to people city routines, like traffic congestion, excessive energy consumption, and pollution (noise and air).

Population growing in urban centers has generated an ever-increasing demand for goods and services, leading to a huge amount of traveling for distribution purposes, resulting in more congestion, pollution, and accessibility reduction. Taking these issues into account, decisions related to the transport systems and policies have become increasingly important. It is, therefore, more and more important to fully understand and study the interactions between the different stakeholders (from suppliers to consumers) and their motivations, to get insights on how to improve urban freight, thus simplifying the associated complex decision processes that involve a multiplicity of conflicting objectives. These factors are a strong motivation for the design of new systematic and analytical approaches that help us improving decisions by the different city logistics agents, to better understand the urban freight flows (Anand et al., 2012).

City logistics is, in fact, the most relevant factor in many economic and social activities, for both inhabitants and companies of many cities. For inhabitants, it involves supplying shops and work and leisure places, delivering services and goods, providing means for waste disposal, etc. For companies established at the boundaries of municipalities, city logistics contributes to creating a vital link between suppliers and customers. There are few activities taking place in a city that do not require urban freight. However, freight is also a major urban life disturbing factor, due to its possible harmful consequences (OECD, 2003).

On one perspective, the urban freight domain can be classified into five components: activities spatial organization, commercial relations, transport services, traffic systems, and intermodal infrastructure.

Moreover, there are four main interacting stakeholders, namely: shippers, carriers, customers, and administrators. Each stakeholder is strongly (directly) linked to at least another one, but weakly (indirectly) linked to the others. The different stakeholders belong to different parts of the city logistics domain. Even if one action by one specific entity may affect the entire domain, in some cases a specific party may only influence the party to which it is closely linked (Boerkamps, 1999).

Some elements of urban freight such as stakeholder involvement, individual and collective objectives, or available means and resources, can be quite important to be included in decision support models. City logistics focus on questions related to the improvement of cities transport efficiency, and at the same time aims at reducing the congestion traffic and environmental impacts (Anand et al., 2012). Therefore, the main objective of city logistics can by viewed as reducing these negative effects, without penalizing social and economic city activities. City logistics also aims at decreasing and controlling the number of vehicles and their dimension, and at increasing movement efficiency, while reducing empty loads mileage. The main idea here is not to consider each shipment, company, and vehicle individually, but instead, as components of an integrated logistics system (Crainic et al., 2009).

City logistics permanently create new challenges for government and local authorities, companies, carriers, and citizens, in their relations with the urban freight. It introduces new businesses and new ways to operate those businesses, and requires a deeper systems understanding, new forms of collaboration and innovative partnerships between the public and the private sectors. For Operations Research and Transportation Science, city logistics creates numerous challenges and opportunities regarding methodological developments and social impacts. Nevertheless, literature reviews reveal that optimization has not been an important component of city logistics until around five years ago. Interesting concepts were proposed, and pilot studies were undertaken, but few models and formal methods have been developed specifically for city logistics design, evaluation, planning, management and control (Crainic et al., 2009). However, in recent years, there has been a growing number of applications of optimization in city logistics (Anand et al., 2012).

In fact, we might say that the overall goal of city logistics is to reduce the goods movement social cost. This goal can be divided into six specific objectives: economy; efficiency; road safety; environment; infrastructure and management; and urban structure (Ogden, 1992). These issues clearly justify the development of decision-making approaches to help solve the related problems. In particular, maximizing the transport utilization will significantly contribute to solving these problems. In this perspective, one approach could be to utilize the space (empty) of passenger transport to move specific types of cargo between cities.

The approach developed in this thesis is in line with these concerns and presents a framework for a new transport system that consists of transporting freight in long-haul passenger vehicles (buses or trains). We believe this approach will contribute to increase transport efficiency and reduce costs, while decreasing the environmental and social impacts resulting from transport traffic. These results will be mainly achieved by the reduction of vehicles circulation around and between cities.

However, it should be noted that not all kinds of products can use this transport solution. Goods that do not need special cares, not offering particular risks and having small dimensions are surely candidates for the approach proposed in this thesis.

The passenger's services considered here are intercity passengers transport. Some initial surveys show that the passenger vehicles baggage compartments generally have significant empty spaces. Therefore, the transport efficiency can increase by filling these spaces (possibly through optimization models based on the *bin packing* problem) with loads that have the same destination of the vehicle. This feature will be the basic principle for the design of the solutions proposed in this work.

We expect that the system developed in this thesis will directly contribute to a decrease of the transport operations costs of some stakeholders (shippers and carriers) and, indirectly, to a traffic reduction in intercity highways and inside cities, with positive environmental and social impacts. The new transport system will take into account the following agents:

- bus stations (that will provide small storage areas for goods);
- passenger vehicles (that will transport freight between origin and destination bus stations);
- suppliers (enterprises that will use the transport services and provide storage areas for their products); and
- customers (enterprises that will pick up goods from the destination bus stations).

In order to optimize the system performance, the problem will be modeled using mixed integer programming. The problem under analysis is similar to one well known mixed integer model from the literature, namely the *multi-commodity network flow* *problem* (Wang, 2018). This combinatorial optimization problem was used in this work as a basis for the development of an innovative mathematical formulation. Figure 1 below summarizes this approach.

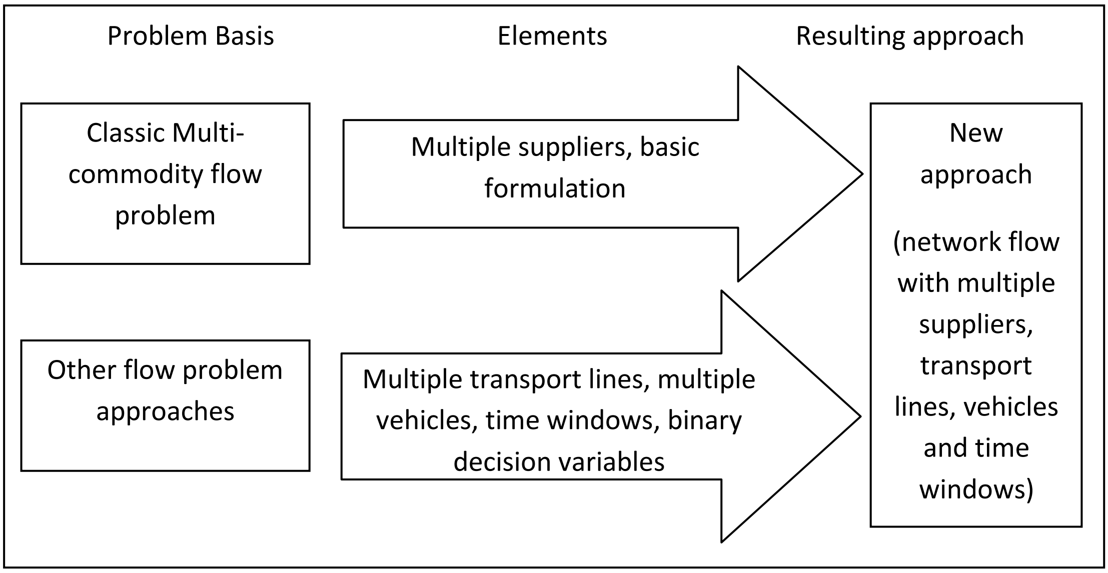


Figure 1 – The new approach for the problem

In general terms, network flow problems aim to optimize some aspect of system operation by moving some objects from a set of origins to a set of destinations, subject to some constraints, as warehouse and vehicle capacities, time windows, etc.

In particular, multi-commodity flow problems consist in moving different types of goods in a network, from suppliers to customers, aiming to optimize some network system attributes. These problems have applications in various areas, such as communication systems, urban traffic systems, railway systems, multiproduct production-distribution systems, or military logistics systems (see e.g. Wang (2018).

Many variants of these problems can be found in the literature, such as linear and non-linear models, capacitated and uncapacitated networks, or fixed-charge network flows. A survey of linear capacitated multicommodity network flow problems can be found in Kennington (1978). Assad (1978) discusses solution techniques for both, linear and nonlinear flow problems. Ouorou et al. (2000) did a literature survey of convex nonlinear multicommodity flow problems. Wang (2018) presented a literature review of multi-commodity network flows problems involving applications (part I) and solution methods (part II).

The approach developed in this thesis is based on a new multicommodity network flow model with time windows, multi-transport lines, and multiple vehicles, consisting in transporting different freight in long-haul passenger vehicles (buses). This approach will contribute to increase transport efficiency and reduce costs, while decreasing the environmental and social impacts resulting from transport traffic. These results will be mainly achieved by the reduction of vehicles circulation around and between cities. In our comprehensive literature review, we did not find any another work with these concerns.

The problem under study can be represented by a graph with a set of nodes (passenger transport terminals) and arcs (passenger transport lines). Decisions are related to the number of goods to be moved between the nodes, by using the arcs in such a way that total costs are minimized. The resulting model will have a high complexity due to a large number of decision variables and constraints mainly related to vehicle capacities. As the two above referred basic models are *NP-hard*, our model is also expected to be *NP-hard*, making it impossible in practice to solve it to optimality by using an exact method. Therefore, heuristic techniques will be developed, to produce satisfactory solutions in reasonable computational times.

Several tests were run for theoretical instances, for two minimization objective functions: time and cost. In the "cost" tests, and for small problem instances, optimal results were obtained with good computational times. When "time" was the objective function, quite good results were obtained for small instances (and with a computational time of 7200 seconds). For large instances, no optimal solutions could be found, for any of the objective functions. Therefore, it is clear that, for these large instances, we need powerful heuristic techniques in order to produce satisfactory solutions in reasonable computational times.

Accordingly, we have designed and implemented two heuristic approaches in this doctoral project: a reduction heuristic here identified as *"size reduction"* and a "LP-and-fix" relaxation heuristic. These approaches were developed using the concert technology for the C++ language and the CPLEX optimization environment. Several results were run for the same class of instances and quite promising results were obtained.

Therefore, the main contributions of this work to the knowledge in the city logistics literature can be identified as the development of a new problem idea, and a methodology to support its resolution (mixed integer linear programming). Finally, the heuristic techniques will work to find good solutions to the problem in low computational time.

1.2. Thesis objectives and research questions

The main purpose of this doctoral thesis is to develop a framework for managing urban freight flows in a network, minimizing total costs, and satisfying all the demand. The goods considered for transportation in this context are products with no risk characteristics. Using an already existing (bus) network is surely an interesting alternative, as transportation costs can be significantly decreased, since vehicles are already going to the specifically required destinations, transporting passengers, independently of having or not having freight allocated.

In this context, the problem can be approached hierarchically, as follows:

• ***strategic problem****:* consists in designing the network, and describing the network operation, thus proposing a specific business model. This business model should specify the whole system operation and guarantee its feasibility. It should also establish the role of each agent participating in the network, and how their actions are interrelated.

• ***tactical problem***: related to fleet sizing and mix definition. Questions such as demand by service, vehicles capacities, and service time windows can be raised at a tactical level. Naturally, the model structure will be built based on the business model designed at a strategic level. This will, given a total trips capacity, help to identify what will be the demand possible to be attended, and which operations related to the time windows are needed to realize freight transshipments in bus stations.

• ***operational problem***: defining paths in the network. An optimization model will be created to determine the set of paths that minimizes the total costs and travelling times of the network, establishing the best way to operate the system in the short term. The parameters to run the system will be obtained from legacy or internal databases, based on the tactical vision. In this way, the produced solutions will be more consistent with reality, thus providing a better network operation.

Figure 2, below, shows the derivation of the proposed approach system, concerning the three hierarchical levels, as problem nature, system conception, and method used to deal with the problem.

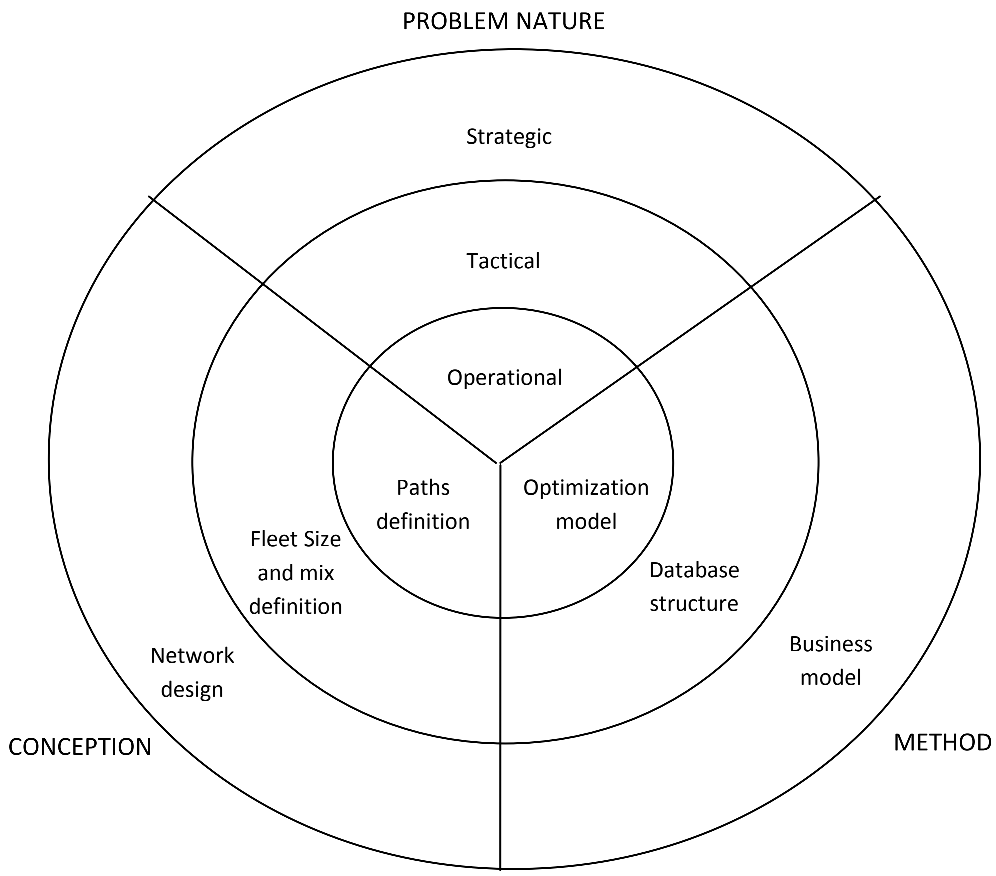


Figure 2 – Proposed approach system.

Each category tackles a different feature of the approach. The strategic problem deals with the formulation of a new business model involving the network design, while the tactical problem deals with information related to the database structure, determining the fleet size and its composition. Finally, the operational problem deals with the development and resolution of the optimization model, that will define the set of paths used to make the system operate. These three approaches are the main contributions of this work.

In this problem, we will specifically decide how freights will be transported from one point in the network to another point. Hence, for each cargo, we must be able to choose one specific path from all those paths that are available, and determine the goods associated with each flow. Costs to be minimized have two main components: a) "fixed" costs, per unit of goods stored in bus terminals; and b) unit operating costs for transport, that will vary according to the distance and the quantity transported. The initial assumption is that, if the network is economically viable for passengers, it should still be more efficient if freight is added to the system.

However, as identified by our study, such a system has some practical limitations, namely:

- vehicle capacity (with space in the baggage compartment of the vehicle being divided by passengers' baggage and cargo, requiring a careful sizing of that compartment);
- the difficulty to fully satisfy demand (should we assume that the total demand is less than or equal to the total system capacity?); and
- the use of storage facilities at stations (that are normally based on the total physical transport capacity, and should not, therefore, be a primary concern).

In the planning process, and once the network operation maximum capacity has been established, goods will be gradually allocated to vehicles. Regarding system organization and management, operational planning will be performed daily, but plans will be produced a couple of days before the execution, to allow the information consolidation related to the inputs of the optimization model.

Goods that exceed the system estimated maximum capacity should be moved to the next planning period with available capacity, with the associated customer being promptly informed (however, these goods will have a higher delivery priority). Warehouses will be managed following a FIFO (First In, First Out) policy, organized by arrival order and not by request order (arrived before, dispatched before).

In order to define, as much as possible, the scope of the doctoral project, we will tackle the above-referred problem, considering the following assumptions:

- The logistic context of large urban centers is constantly affected by high volumes of traffic, environmental impacts (such as noise and visual pollution), as well as economic inefficiencies, arising from the difficulties in managing complex materials and goods. Measures should be taken to minimize these negative impacts.

- Some goods do not need special cares during transportation (having no special risks concerning perishability, fragility, tendency to explode, etc.) and can be moved in a passenger's vehicle baggage space.

- In general, in any trip, the passenger vehicle baggage space is not fully-filled. There is an average proportion of empty space which can be estimated in advance. This space can be used to carry other loads (cargo loads).

- The methods and procedures developed in this doctoral project are expected to lead to a significant decrease in urban road transport. We believe this will result in the generation of social, economic and environmental benefits, proving the validity and positive impacts of the research.

- Depending on the specific urban scenario under consideration, the relative importance of the different aspects will have to be taken into account. Namely, this includes transportation modes, legal aspects, mobility needs, vehicles frequency, products availability, spatial locations, etc.

1.2.1. Research questions

Taking into account all the above considerations and assumptions, and based on the research gaps identified through a comprehensive literature review (see next sections), the following research questions have been formulated:

1. How to develop a transport system network that integrates urban freight with passengers' transport? How can this problem be fully characterized?
2. Which optimization models can be used to design and manage such a network?
3. Will it be possible to solve the optimization models by exact methods, and therefore find optimal solutions in an acceptable amount of time? Otherwise, which heuristic techniques should be applied to find satisfactory solutions efficiently?
4. How can the developed methods and techniques be applied to passenger transport systems in reality?

This doctoral project aims at responding to these questions, and a detailed methodological approach has been designed for this purpose (see next sections of the document).

In line with this main work stream, some relevant deliverables are expected that will hopefully have a considerable practical impact. Namely, we will:

1. develop the concept and structure of a transport system network, integrating urban freight and passengers transport;

2. design a mathematical programming model to represent and optimize the system;
3. develop heuristic techniques for solving the proposed model;
4. apply the proposed approach for solving real world problems (and assess it in a real case study).

1.3. Thesis overview

This doctoral thesis is organized in eight chapters: this introductory chapter and more seven chapters, briefly presented in the next paragraphs.

Chapter 2 presents a general literature review on city logistics, the sharing economy, and multi-commodity network flow problems, as a way to set the ground for a structured, integrated research project.

In Chapter 3 a set of methodological choices and assumptions are presented, and the main features of the an innovative network transport system proposed. Moreover, the adopted methodology and the case study are described.

Chapter 4 presents the multi-commodity network flow problem with multi-transport lines, multiple vehicles and time windows. A mathematical model for this problem is also presented and a simple problem representation proposed, in order to provide a better undestanding of the problem.

Chapter 5 presents our solution approaches for the proposed network flow problem, based on size reduction, a LP-and-fix procedure, and a hybrid method. Solution methods are proposed to tackle the problem.

Chapter 6 describes how the developed approaches were validated and tested in a set of representative randomly generated instances. First an instances generator is presented. Then, results are analyzed and discussed for the different methods applied in dealing with the two proposed problem objective functions: cost and time.

Chapter 7 presents the case study general information, the data gathering process, the set of assumptions needed for the study, and the methods proposed for the two objective functions (cost and time). Results are analyzed and discussed.

Finally, Chapter 8 presents the main achievements and contributions of this research work, the conclusions of the thesis and its limitations, and some suggestions for future work.

Chapter 2

State of the Art

Summary: This chapter reviews research studies for some themes that seem to be relevant for the problem under study, especially city logistics, network design, the sharing economy, and multi-commodity network flow problems. Here some characteristics of a city logistics system are highlighted, based on a literature review that was made aiming to ground this research. An analysis of some works in city logistics areas was made, classifying the published studies in a set of eight categories. Then, some variants of the multi-commodity network flow problem were analyzed. The relations of city logistics and the sharing economy are explored, trying to explore similarities between airline's companies alliances and urban freight. Finally, the literature gaps are highlighted.

2.1 City logistics

According to Taniguchi et al. (2001), city logistics is the process of optimizing all activities related to urban flows of materials, taking into account the social, environmental, economic, financial and energetic impacts caused by urban freight. According to these authors, city logistics initiatives are indispensable to solve urban freight problems including high levels of traffic, negative impacts to the environment, high energy consumption and labor shortages.

For Thompson et al. (2001), city logistics is a distribution process based in integrated planning that promotes innovative schemes aiming to reduce the urban freight total cost (including economic, environmental and social costs). The city logistics systems provide a planning scheme that involves the establishment of partnerships between the public and private sectors. Therefore, city logistics refers to techniques and projects that use these partnerships to reduce the total number of vehicle trips in urban areas, or to minimize their negative impacts.

2.1.2. Functions and objectives

Taniguchi et al. (2001) state that city logistics is related to the optimization of logistics systems, considering the costs and benefits for both the public and private sectors. On the one hand, in the private sector, there are shippers (factories, wholesalers and retailers) and logistics operators (carriers and storage companies), aiming to reduce warehouse management costs. On the other hand, in the public sector, there are governmental (national, state and municipal) authorities wanting to decrease traffic congestion and environmental problems. Residents (consumers) are the target group of the activities of both these sectors in city logistics. Taniguchi et al. (2001) highlight four groups of stakeholders, as illustrated in Figure 3.

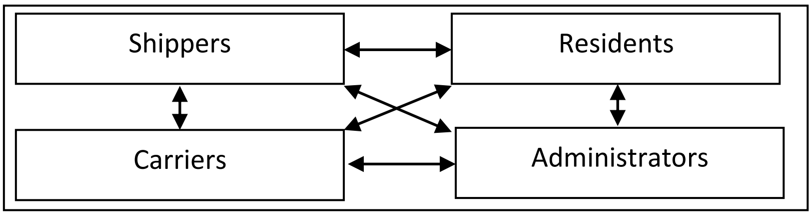


Figure 3 – City logistics stakeholders.
[source: adapted from Taniguchi et al. (2001)]

According to Anand et al. (2012), urban freight stakeholders can be divided into two categories. The first category includes actors in the public sector, including transit authorities, infrastructure, municipalities, ports, and terminal rail authorities, etc. (these actors can generally be viewed by as the *"administrators"*). It may be noted that users of the road and the locals are not directly involved in urban freight, but their goals are aligned with those of the actors in the public sector. In the second category, we have private sector stakeholders, including producers, suppliers, shippers, intermediate traders, trucking companies, truck drivers, shopkeepers, receivers, etc. This long list of private agents can be simplified by just considering the *shipper*, the *transporter* and the *receiver*, according to the specific transportation activities stage. For Crainic et al. (2009), the involvement of public institutions, local authorities, and public-private partnerships are strongly significant and more widely disseminated than before.

Under "supply chain management," companies try to optimize total logistics costs, with urban freight being just a small part of the whole systems. The *administrator* is also responsible for city maintenance and economic development. For efficient city logistics, the interests of all stakeholders must be taken into consideration. Even the *administrator*, who is not the main decision-maker in the process, can significantly affect other stakeholders decisions, by enforcing different policy measures. In contrast to the private agents, the *administrator* is in general interested in achieving a set of overall objectives, particularly reducing the social costs (Ogden, 1992).

The markets that define the interactions and interfaces between stakeholders are called *descriptors.* For example, in the *commodity market,* there are freight generation, commodity flows, and industry structure issues. In the *transport service market,* there are vehicle loading, vehicle design, trip generation, and transport cost issues. In the *traffic service market,* there are traffic design, traffic flow, and pollution level, as descriptors. Finally, in the *infrastructure market,* land use, location, building, and site design, and modal changes are the descriptors (Anand *et al.*, 2012).

In city logistics, modeling may be viewed as a way to represent a system in detail, and each specific model can represent different aspects of the real system, and convey different, complementary perspectives. A specific perspective depends directly on the objectives of the model and on the means to achieve those objectives, and it should reflect the different strategic points of view (Anand *et al.*, 2012).

There are several main *perspectives* normally considered in urban freight modeling processes: a) the planner, who aims at making efficient use of the infrastructure; b) the technology, such as Geographical Information Systems – GIS, Intelligent Transport Systems – ITS, Intelligent Transport Contracts – ITC, or Logistic Information Systems – LIS, allowing information sharing in real time, helping to make a better use of urban freight in delivery and distribution activities, and increasing efficiency; c) a behavioral perspective, focusing on the ability of the stakeholders in making decisions, in different conditions; d) policy, with the implementation of measures aiming at environmentally and socially improving the efficiency and sustainability of transport activities; and e) a multi-actors perspective, reflecting the complexity of the multiple stakeholders decision making processes, with impacts along the whole chain (Anand *et al.*, 2012).

According to Crainic et al. (2009), the logistics function aims at analyzing, planning, managing and coordinating, in an integrated way, the physical and financial flows (e.g. materials, goods, and money) as well as the electronic flows (e.g. information, and decisions), with the multiple involved partners. It is in this perspective that the "city logistics" term has been used, to emphasize freight consolidation, departing from different shippers with the same vehicle, and also as a tool to support urban freight coordination.

For Browne et al. (2005), *consolidation* and *coordination* are fundamental concepts in city logistics. Consolidation activities are usually performed by the so-called *city distribution centers* (CDCs). The CDC concept is close to the intermodal platforms and load villages, which provide the means for load transfer between vehicles with different characteristics and shapes, as well as for goods storage, selection and consolidation or deconsolidation. A CDC works as a facility close to city access or ring road or is a part of a bus, air, rail, or port terminal. CDCs should, therefore, be seen as platforms enhanced to provide coordinated and efficient flows in urban areas. They play an important role in providing an urban freight better organization, and are used as a key component in most city logistics projects currently under development.

2.1.3. System features

Crainic et al. (2009) report that one-echelon city logistics systems operate just one consolidation-distribution activities level, with distribution routes starting at the CDC and distributing goods directly to the customers. One or two-echelon distribution systems are used to improve the city logistics system fluidity. One-echelon systems are generally subject to specific logistic features of the cities. The influence area is relatively small and close to the city outskirts where the CDC is located. In the two-echelon consolidation and distribution systems, shipments are brought by large vehicles and first consolidated in a CDC, this being the first system level. Then, later (second level), they are transferred to smaller systems that are more appropriate for activities in the city center, with the deliveries to end users.

As Crainic et al. (2009) report, logistic systems are not very performant when single operators are located inside the large cities. City centers are generally large and distant from the CDCs, these being normally close to the city peripheries (most of these facilities were not initially located or designed specifically to be used for city logistics). In many cases, the city center has a high population density, with commercial structures, administrative and cultural activities being served by a dense network of narrow, usually congested streets. Parking spaces are paid and under vehicle size strict regulations. One direct distribution form “CDC – final customer” is usually very long and unsatisfactory.

A first option to deal with this problem is to use large vehicles, offering low unit transportation costs (when fully loaded), and operating long trips at one time. This in typically in conflict with the customer delivery time windows, and many deliveries are required within short time intervals, implying an inefficient vehicle capacity use, most of the traveling being performed with low loads. Besides, whenever the streets configuration and city access regulations make this a viable option, the massive presence of large vehicles in the city center does not at all contribute to the population welfare. A second option is to use smaller vehicles that are more appropriate for the traffic conditions of the city center, requiring however a very large fleet, with high operation costs, additional labor (drivers), and the need to acquire a large number of vehicles. Moreover, congestion may increase significantly.

Some surveys discuss and quantify a set of critical issues related to the low average of vehicle shipments and the high number of empty trips. It seems, from these studies, that traffic and parking regulations are unable to deal with the problem properly. The construction of underground automated systems, dedicated to urban freight, has been proposed as a means to reduce the number of vehicles moving in urban areas, but the massive required implementation investments make this alternative impractical in most cases (van Duin 1998; Oishi and Taniguchi 1999). However, it also seems that significant gains can be achieved through distribution rationalization, resulting in much better use of vehicles (Crainic et al. 2009).

Taniguchi et al. (2001) state that modeling plays a central role in the design of city logistics solutions, by allowing the estimation of numerous change effects without the need of modifying the current system. These authors also point out the limitations of classical exact optimization methods, to incorporate the adequate realism and complexity of real systems. Approximate, heuristic methods are therefore developed in practice.

2.2 Studies classification

The comprehensive literature review performed in this research allowed us to divide the contributions in city logistics into the following eight broad groups (or categories). It is important to highlight that this classification just took into consideration studies and applications from the broad areas of logistics and operations research that have a close relationship with urban environments.

1. ***City Logistics and trend.*** These contributions collect general information and practices in city logistics from all around the world, identifying new trends, gaps, and perspectives, in an attempt to organize the available material, and the main theoretical and practical approaches. These approaches are important to understand the evolution of city logistics as a scientific field, and encompass review studies, other classifications, and exploratory approaches. This category includes: classification reviews (Anand *et al* 2012, Benjelloun et al, 2010, and Ambrosini & Routhier, 2002); trends and evolution perspectives (Benjelloun & Crainic 2009, and Taniguchi et al, 2010); and concept development approaches (Ogden, 1992, Emke, 2012, Thompson et al. 2001, and Taniguchi et al, 2001).

2. ***Logistics Network Design.*** In general, this category is related to network flow problems. In most of the cases, the objective is to minimize trip costs and duration, as well as to avoid vehicle congestion on the network. Some approaches involve decisions related to pricing, planning of integrated logistics, and traffic simulation. This group of studies includes problems such as: multimodal transportation networks (Wu, et al. 2011); car rental logistics problems (Fink & Reiners, 2006); logistics land use (Woudsma, et al. 2008); promotion-sensitive grocery logistics systems (Iyer & Ye, 2001); integrated logistics planning (Li, et al. 2002); city logistics planning (Li, et al. 2008 and Taniguchi & Van Der Heijden, 2000); or inter-organizational systems (Steinfield et al, 2011).

3. ***Location.*** A significant group of studies addresses problems related to facilities location, aiming at providing strategic advantages to city logistics operations. They include problems such as: hub location in transportation networks (Gelareh & Nickel, 2011); depot location in car sharing systems (Correia & Antunes, 2012); the design of paper recycling networks (Schweiger & Sahamie, 2013); the location of public logistics terminals and transport terminals (Taniguchi et al,

1999; Zhongzhen & Weiqing, 2007); or the location of city coach stations (Zhang, et al., 2011).

4. ***Routing.*** This category includes a set of approaches dealing with routing problems. In these problems, there is a set of vehicles with a given capacity and a set of goods that must be moved through a network from given origins to destination points. The objective is in general to minimize total costs. This group includes cases and problems such as the two-echelon VRP (Perboli et al., 2010; Perboli et al., 2011; Hemmelmayr et al. 2012; Anily & Federgruen 1993; Crainic et al., 2009); commercial activity routing (Figliozzi, 2006; Figliozzi, 2007); large scale vehicle routing problems (Kytöjoki, 2007); a VRP with time windows and coordination of transportable resources (Lin, 2011); dynamic routing under recurrent and non-recurrent congestion (Guner et al, 2012); interconnected vehicle routing problems in a hospital complex (Kergosien et al, 2013); multi-depot VRP with heterogeneous vehicle fleet (Salhi et al, 2014); the carrier's optimal bid generation problem (Lee et al, 2007); multi-item inventory routing problems (Huang & Lin 2010); VRP with soft time windows in a fuzzy random environment (Xu et al, 2011); a VRP with Urban Policy restrictions and the environmental issues (Quak & Koster 2009); a VRP with multiple synchronization constraints (Drexl, 2012); auto-carrier transportation problems (Tadei, 2002; Agbegha 1998); logistics-oriented vehicle routing problems (Bell & Griffis, 2010); a VRP with simultaneous pick-up and delivery service (Montané & Galvão, 2002).

5. ***Location-routing.*** These problems are a mix of location and routing problems, merging their traditional objectives, and combining their constraints. Here the main objective is to locate facilities in the logistics network, to improve vehicle routing. The following problems and approaches are in this group: a two-echelon location-routing problem (Nguyen et al., 2012); a two-echelon capacitated location-routing problem (Contardo et al., 2012); conversion of "brick mortar" retailing to the ''click-and-mortar'' (Aksen & Altinkemer, 2008).

6. ***Routing-scheduling.*** As above, this group merges two problem classes: routing and scheduling. Here the main objective is to schedule vehicles, according to their physical characteristics and time windows, to find the best routing solutions. Examples of work along this line of research: city-courier routing and scheduling problems (Chang & Yen, 2012); vehicle routing and scheduling problems with soft time windows (Qureshi et al., 2009); vehicle scheduling and routing with drivers' working hours (Goel, 2009).

7. ***Supply Chain Management.*** This category includes approaches that, in general, aim at understanding, improving and evaluating supply chain enterprises integration. Techniques are presented to add value to all chain participants or to analyze the global supply chain performance. These studies address problems

such as: interrelationships between the supply chain integration scope and supply chain management efforts (Jayaram et al, 2009); supply chain performance (Cigolini et al, 2011); impact evaluation of supply chain initiatives (Mishra & Chan, 2012); supply-chain uncertainty (Simangunsong et al, 2012); purchasing and supply management (Schoenherr et al, 2012); risk mitigation in supply chain digitization (Xue et al, 2013); or supply chain information sharing (Yu et al, 2001).

8. ***Urban freight.*** This broad category covers the approaches for solving logistic problems related to urban freight movements, inside cities, including the improvement of delivery systems, policies, and actions for decreasing traffic, the use of multimodal freights, and passengers transport optimization, among others. The main goal here is to reduce the negative impacts of city logistics. Examples of work in this area: freight transport policy in urban areas (Anderson et al, 2005; Hesse, 2004); integrative freight market (Holguin-Veras, 2000); conditions for off-hour deliveries and the effectiveness of urban freight road pricing (Holguin-Veras, 2008); urban commercial movements (Hunt & Stefan, 2007); daily vehicle flows for urban freight deliveries (Muñuzuri et al, 2011); container movement by trucks in metropolitan networks (Jula et al, 2005); dynamic resource allocation for demand-responsive city logistics distribution operations (Sheu, 2006); micro-behavior commodity transport (Liedtke, 2009); a transportation network with a downtown space reservation system (Zhao et al, 2011); a commercial vehicle daily tour chaining (Ruan et al, 2012); multimodal freight transport networks (Yamada et al, 2009); evaluation of the behavior of several stakeholders (Taniguchi & Tamagawa, 2005); vehicle scheduling under uncertain traffic (Wu et al, 2007); a scheduling model of logistics distribution vehicles (Yan et al, 2008); definition of sustainability from an actor's perspective (Behrends et al, 2013); transportation systems for congested urban areas (Crainic et al, 2004); city logistics measures using a multi-agent model (Tamagawa, 2010); city logistics measures and connected impacts (Russo & Comi, 2010); or urban transport systems based on resident surveys (Witkowski, 2012).

Most of these approaches blend city logistics with traditional logistics techniques, thus adding value regarding costs, efficiency, lead time, or service level. These are important business objectives, and they reflect the need to simultaneously deal with important issues in city logistics, such as high traffic levels, negative environmental impacts, high energy consumption, and labor shortages. These goals together should, therefore, be taken into consideration when dealing with city logistics problems.

Several approaches were developed in the literature to deal with a multi-commodity network design problem and its variants. In this section a brief literature review related to this problem is presented, and the associated solution techniques are briefly described. The references are presented in chronologic order.

Kirby et al. (1986) present an approach that deals with natural resource and transportation network investments, represented by two models for multiple commodities and periods: a transshipment model with fixed-charge arcs and a land allocation model. To solve this problem, the authors use two different approaches. When the size of the mixed-integer program is relatively small, they use exact methods with state-of-art optimization software packages. For large instances, a heuristic procedure based on solving an LP relaxation of the problem with successive improvement attempts was developed.

Helme (1992) developed a computer-based decision tool to deal with the reduction of air traffic delay in a space-time network. The problem consists in evaluating the impact of airway capacities upon traffic, from multiple origins to multiple destinations. The problem was modeled as a multicommodity minimum cost flow problem over a network in space-time.

Farvolden et al. (1993) developed an approach based in both primal partitioning and decomposition techniques to solve the multicommodity network flow problem. The methodology consists in simplifying the computations required by the simplex method.

Barnhart et al. (1993) developed a network-based primal-dual heuristic solution approach for large-scale multicommodity network flow problems. The authors found out that primal-dual and price directive algorithms (exact solution strategies) are unable to achieve even an initial solution for this problem due to excessive memory requirements. However, the network-based heuristic determines an optimal solution.

Barnhart et al. (1994) present a partitioning solution procedure for large-scale multicommodity flow problems, using a cycle-based problem formulation and column generation techniques to solve a series of reduced-size linear programs in which a large number of constraints are relaxed.

Farvolden and Powell (1994) present a local-improvement heuristics for a service network design problem. The scheduled set of vehicles departures are modeled as a multi-commodity network flow problem. In this way, the heuristics are structured in two steps: one for dropping a scheduled service, and another for introducing a new service. Both are based on subgradients derived from the optimal dual variables by the shipment routing subproblem.

Cruz et al. (1998) developed a branch and bound algorithm approach to solve the uncapacitated fixed-charge network flow problem optimally.

Frangioni and Gallo (1999) describe a cost decomposition approach for the linear multicommodity min-cost flow problem. On this methodology, the mutual capacity constraints are dualized, and the resulting lagrangian dual is solved with a dual-ascent algorithm belonging to the class of bundle methods.

Gabrel et al. (1999) developed an exact solution procedure for the multicommodity network design problem with general discontinuous step-increasing cost functions, including single-facility and multiple facilities capacitated network loading problems, using a standard linear programming software. The procedure is a specialization of the general Benders partitioning procedure.

Crainic et al. (2000) present an efficient procedure to solve the fixed-charge capacitated multicommodity network design problem, using a tabu search framework that explores the space of the continuous flow variables, by combining pivot moves with column generation, while evaluating a mixed integer objective. In this way, they determine tight upper bounds on the optimal solution of realistic size problem instances.

Barnhart et al. (2002) developed an approach to solve a particular service network design, the express shipment delivery problem. They developed models and a solution technique designed specifically for large-scale problems with time windows. The solution approach consists in dividing the service network in two subproblems: route generation and shipment movement. The first problem is solved using a brach-and-price-and-cut algorithm. The shipment movement subproblem is a large scale integer multicommodity network flow model with side constraints and is solved using a branch-and-price algorithm to find the network shortest paths.

Holmberg and Yuan (2003) present an efficient column generation approach for solving the multicommodity network design problem with side constraints on paths. In this approach, the solutions are built up successively by path generation, and the objective is to find the set of shortest paths.

Alvarez et al. (2005) developed a grasp embedded scatter search to solve the multicommodity capacitated fixed charge network design problem.

Topaloglu and Powell (2006) present a stochastic and time-dependent version of the minimal cost multicommodity flow problem. The authors propose an interactive, adaptive dynamic-programming-based methodology making use of linear and nonlinear approximations of the value function.

Lim and Smith (2007) deal with a network interdiction problem as a multicommodity flow network. According to the authors, an attacker disables a set of network arcs to minimize the maximum profit that can be obtained from shipping commodities across the network. The interdiction can be discrete (concerning the choice of each arc) or continuous (related to the arcs capacities). To deal with the discrete problem, a linearized model for the optimized network was developed and compared to a penalty model that does not require linearization constraints. In the continuous case, a heuristic algorithm for optimal partitioning was developed, used to estimate the objective function value.

Oimoen (2009) presents three contributions for solving highly dynamic capacitated multicommodity network flow problems. First he develops an ant colony algorithm to solve the static problem with weak constraints. Then another algorithm is used to adjust the exploration parameter of the solution space dynamically. Finally a distributed approach is proposed, replacing the previous centralized solver.

Aloise and Ribeiro (2010) present heuristics based on the shortest path and maximum flow algorithms, combined with adaptive memory to obtain an approximate solution to the multicommodity network design problem in the framework of a multi-start algorithm.

Guardia (2010) designed a numerical implementation of the primal-dual interior-point method to solve the linear multicommodity network flow problem. According to the authors, in this approach, at each iteration the corresponding linear problem, expressed as an augmented indefinite system, is solved by using the AINV algorithm combined with an indefinite preconditioned conjugate gradient algorithm.

Kim et al. (2011) consider the fixed-charge capacitated multicommodity network design problem with turn penalties. A mixed integer programming model is presented, and the authors developed a two-phase heuristic algorithm to solve the problem. The approach consisted in building an initial flow path network by a construction method, that was then improved with an iterative approach.

Kleeman et al. (2012) developed a multiobjective evolutionary algorithm to solve the multicommodity capacitated network design problem. According to the authors, this variation represents a hybrid communication network with multiple objectives including costs, robustness, vulnerability, delays, and reliability. They used a modified and extended nondominated sorting genetic algorithm with a novel initialization procedure and mutation method, to deal with the highly constrained problem features. The obtained results were good, and the algorithm performs very efficiently.

Zantuti (2013) presents linear capacity and heuristic algorithms for multicommodity flow problems in computer networks engineering, aiming to minimize shipping costs.

Malairajan et al. (2013) deal with the multicommodity network flow problem and with a variant of it named bi-objective resource allocation problem, with bound and varying capacity. To solve both problems, the authors developed a recursive function inherent genetic algorithm obtaining good quality solutions.

Tadayon and Smith (2013) developed two linearization techniques to solve the min-cost multicommodity network flow problem, proposing a pair of lower an upper bounds formulation. The solution method is based on integer programming and cutting plane techniques.

Lagos et al. (2014) developed a hybrid metaheuristic approach combining tabu search and genetic algorithms to deal with a capacitated multicommodity network flow problem. While the tabu search acts as the main algorithm, the genetic algorithm is used to select the best option among the neighbors of the current solution.

Masri et al. (2015) present a multi-start variable neighborhood search to solve a capacitated single path multicommodity flow problem.

Wei et al. (2016) worked on the multi-source single-path multicommodity network flow problem, and developed an effective simulated annealing based metaheuristic to minimize the network total transportation cost.

Lin (2017) presents a class of multicommodity flow problems with commodity compatibility relations among commodities used at each network node. To solve this problem, the authors use a node-family branching technique, that removes incompatible commodities at nodes, by a branch-and-bound algorithm.

Table 1 bellow shows an overview of the multi-commodity network flow problem approaches presented in this section, their variants, the respective solution methods (classified as exact or heuristic approaches), objective function type (minimization or maximization), arc type (capacitated or uncapacitated) and finally, the problem features (fixed charge costs and time windows).

There is a slight majority of papers addressing the multicommodity network flow problem and its variations by heuristics techniques. Probably this is due to the complexity of the problem when large instances are considered. We can also notice that the multicommodity network flow problem has many variations and it is used to help in modeling many real problems. This is due to the fact that the model is very adapt to different real situations.

In a large majority of these studies, the objective function is a cost minimization, instead of a maximization of arcs flow. We can also notice that in a majority of the cases, capacitated arcs were used instead of uncapacitated arcs, thus showing the need of approaches that are closer to reality.

Finally, it should be noted that from the 28 studies reported in this literature review, just 10 considered fixed charge costs and only 4 dealt with time windows. It seems therefore that these two features of multicommodity design flow problems are still explored in the literature, in a quite limited way.

Table 1 – An overview of the multi-commodity network flow problem approaches

Reference	Problem variant	Solution Approach		Objective		Arc Type		Problem Features	
		Exact Method	Heuristic Method	Min	Max	Capacitated	Uncapacitated	Fixed Charge	Time Windows
Kirby et al. (1986)	Natural resource and transportation network investments		X	X		X		X	
Helme (1992)***	Reduction of air traffic delay in a space-time network	X		X		X			X
Farvolden et al. (1993)	Multicommodity network flow problem	X		X		**	**		
Barnhart and Sheffi et al. (1993)	Multicommodity network flow problem		X	X	X	**	**		
Barnhart et al. (1994)	Multicommodity flow problem	X		X		**	**		
Farvolden and Powell (1994)	Service network design problem		X	X		**	**		
Cruz et al. (1998)	Uncapacitated fixed-charge network flow problem	X		X			X	X	
Frangioni and Gallo (1999)	Linear multicommodity min-cost flow problem	X		X			X		
Gabrel et al. (1999)	Multicommodity network design problem with general discontinuous step-increasing cost functions including single-facility and multiple facilities capacitated network loading problems	X		X		X			
Crainic et al. (2000)	Fixed-charge capacitated multicommodity network design problem		X	X		X		X	
Barnhart et al. (2002)	Express shipment delivery problem	X		X		**	**	X	X
Holmberg and Yuan (2003)	Multi-commodity network design problem with side constraints on paths	X		X		X			
Alvarez et al. 2005	Multi-commodity capacitated fixed charge network design problem		X	X		X			
Topaloglu and Powell (2006)****	Stochastic and time-dependent version of the minimal cost multicommodity flow problem		X		X	**	**		
Lim and Smith (2007)	Network interdiction problem	X	X	X	X	**	**		
Oimoen (2009)	Highly dynamic capacitated multicommodity network flow problem.		X	X		X			
Aloise and Ribeiro (2010)	Multi-commodity network design problem		X	X		**	**		
Guardia (2010)	Linear multicommodity network flow problem	X		X		X			
Kim et al. (2011)	fixed-charge capacitated multicommodity network design problem with turn penalties		X	X		X		X	X
Kleeman et al. (2012)	Multicommodity capacitated network design problem		X	X		X		X	X
Zantuti (2013)	Multicommodity flow problems in computer networks engineering		X	X	X	**	**		
Malairajan et al. (2013)	multicommodity network flow problem and bi-objective resource allocation problem with bound and varying capacity		X	X		X			
Tadayon and Smith (2013)	Min-cost multicommodity network flow problem	X		X			X	X	
Lagos et al. (2014)	Capacitated multicommodity network flow problem		X	X		X		X	
Masri et al. (2015)	single path multicommodity flow problem		X	X		X			
Wei et al. (2016)	Multi-source single-path multicommodity network flow problem		X	X		X		X	
Lin (2017)	Multicommodity flow problems with commodity compatibility relations	X		X		**	**		
	TOTAL	**12**	**16**	**27**	**4**	**14**	**3**	**10**	**4**

*** This information was not presented in the paper.*

2.3 City logistics and the sharing economy

Sharing economy applications are a good way of accomplishing the previously mentioned goals. According to Botsman (2013), a sharing economy is any marketplace that uses the internet to bring together distributed networks of individuals to share or exchange otherwise underutilized assets. Thus, it encompasses all types of goods and services shared or exchanged for both monetary and nonmonetary benefit. The sectors in which the sharing economy has seen substantial growth and disruption include transportation, hospitality, dining, goods, finance, and personal services (Koopman et al., 2014).

The approach to be developed in this research project can be viewed as an example of sharing economy application. We aim at designing a collaborative transport system in which consumer goods (that do not have risk characteristics) are moved between cities by passenger transport services. Such a system will be based on the allocation of palletized or fragmented (in boxes) freight in vehicles cargo hold empty spaces. In this way, a collaborative system is created that aims to reduce transport costs and decrease the number of vehicles on the road.

In this project, enterprises are expected to develop a mutual collaboration scheme in a sharing economy perspective. Suppliers bring their goods (that have a predetermined destination point) to an intermediate city collection point, located at a strategic place. Then, the consolidated goods follow in a small truck to a bus station, and there they are placed in an intermediate storage area. After this, loads are allocated to a given transport, according to the specified destination, and a decision support tool will help minimize transportation costs.

This system will, therefore, require a strong and adequate coordination of all the involved agents. Problems can be minimized with the development of a conceptual model covering all system aspects, such as the number of goods, time windows, dynamic participation of the different agents, and vehicle allocations. Moreover, several constraints must be respected, such as those associated to vehicles capacities, or imposed by supply and demand on the movements of products.

The adoption and operation of this system will generate gains in economic, environmental and social terms, since it will hopefully lead to significant cost reductions, to less traffic between and inside cities, and to a pollution decrease (noise and visual). By reducing logistic costs, prices to the final consumer will also be decreased.

The system will involve the direct participation of quite different stakeholders. In the city logistics literature, these stakeholders are generally classified as shippers (supply and demand enterprises) and carriers (passenger’s vehicles, passenger’s terminal logistics operators, and small truck transport enterprises). However, there is also an indirect participation of administrators (public authorities) and influence in the potential system clients (final consumers) who will benefit in terms of prices, traffic, and pollution.

Enterprises can behave in quite different ways to develop sharing economy practices. According to Matzler et al. 2015, these behaviors can be classified into six types, as follows: (1) by selling the use of a product rather than its ownership; (2) by supporting customers in their desire to resell goods; (3) by exploiting unused resources and capacities; (4) by providing repair and maintenance services; (5) by using collaborative consumption to target new customers; and (6) by developing entirely new business models enabled by collaborative consumption.

Gonzalez-Feliu and Salanova, 2012 proposed a framework to define and evaluate collaborative urban transportation systems, divided in six modules: a knowledge management system, a scenario simulator, a transportation management system, an environmental module, a risk factor estimation module and a multi-criteria decision support method.

Zhang et al. 2004 state aviation companies have made alliances in the same sector in order to better explore the mixed services between cargo/passengers in long and short-haul. In this way, air passengers companies can provide cargo services to shippers, traders, manufacturers, and other enterprises, using the belly compartment of a passenger aircraft. Coupling these solutions with the *just-in-time* pressure and vertical integration of the logistics industries, has clearly increased the utilization of express delivery services through passenger/cargo air service.

With the offer of this service through alliances formed between companies in the sector (more and more alliances are being formed today), the profit of companies has grown considerably. In fact, alliances are formed in order to better coordinate the flight departure and arrival times so as to allow time to perform airport movement activities between the combined flights, as well as the possibility of allowing passengers and freight to reach longer destinations, where a company is not able to operate, due to technical, legal or regulatory barriers (Zhang et al. 2004).

According to Billings et al. 2003, air freight and passenger transport differ in three main attributes: demand, vehicle capacity, and ways to optimize those vehicles (see Table 2 below).

According to Yan et al. 2006, the Asian-Pacific area continues to dominate the international air freight market. Many studies have been developed in Taiwan (the center of the region), with these markets becoming more competitive in recent years, forcing companies to search new practices to improve the operations efficiency. These authors developed an approach to improve the operating performance and an integrated scheduling model , with the aircraft management being combined with airport selection, fleet routing and timetables.

Table 2 – Comparison between capacity, demand and optimization attributes related to cargo and passenger airline transport [adapted from Billings et al., 2003]

Attributes	Cargo	Passenger
Capacity	Multi-dimensional - weight, volume, positions	Single-dimensional- seats
	Variable (each flight has different capacity)	Cabin is either fixed or semi-fixed (i.e. movable-curtain cabin)
Demand	Irregular	Comparatively, smooth based on seasons
Optimization	Multi-dimensional	Mostly one-dimensional Itinerary-bound
	Service-level-bound	
	Medium-term commitments - contracts, allocations, block space	
	Multiple routings to meet service commitments	Short-term commitments-bookings
	Operational restrictions	

Hong and Zhang, 2010, developed a study to understand if a high degree of cargo business operating with mixed passenger/cargo airlines improves their operational efficiency. Using Data Envelopment Analysis, and by the observation of 29 airlines (during the period between 1998 and 2002), they concluded that airlines with a high share of cargo business could improve their operations efficiency more than airlines with low cargo share.

According to Gardiner et al. 2005, two very important decisions for an airline cargo operator are the definition of the markets to serve and the airports to operate with these markets. Passenger services have significantly increased in recent years and according to forecasts will continue to increase, making freight operations quite difficult, and leading to more complex decision-making processes that have to consider alternatives to gateway airports.

Gardiner et al. 2005 tried to identify and evaluate the factors that influence the airport choice of freighter airlines, through a questionnaire application responded by 118 non-integrated operating freighter airlines. Table 3 shows the reaction of the respondents when asked what can airports do to attract airlines business, and what factors have led operators to relocate airport.

Table 3 – Airlines expectative about airports choice [adapted from Gardiner et al., 2005].

What can airports do to attract airlines business?	*% of respondents*
Lower fees for landing, handling, and fuel	53
Improve facilities and infrastructure	31
Work with businesses to increase demand	25
Improve handling efficiency	22
Give specific needs of cargo airlines more attention	16
Improve ground transport facilities	13
Give cargo equal priority to passengers	13
Improve labor quality	6
Simplify charging structure	6
What factors have led you to operator relocate airport?	*% of respondents*
Specific demand from the primary customer	67
Better facilities elsewhere	60
Lower charges elsewhere	47
Environmental restrictions	27
Increase in charges	13
More attention to cargo at another airport	7
More business potential in a new region	7
Pressure from the government to move to another airport	7
Lack of capacity for expansion	7

2.4 Literature gaps

In this dissertation, we can view the developed approach mainly as logistics network design, since the modeling approach is based on a network flow problem. In the classic Operations Research (OR) literature, two problems can be taken as a basis for modeling the proposed system: the multi-commodity network flow problem (Wang, 2018), and the fixed-charge network flow problem (Kim & Hooker, 2002).

Moreover, it should be emphasized that the literature on sharing transportation systems integrating passenger transportation and urban freight is still very scarce. As a way to fill these gaps, the contributions of this work aim at:

1. developing a new conceptual framework to describe the integrated passenger and cargo transport system operation;
2. creating a new modeling approach for the proposed integrated problem;
3. developing an algorithmic approach to solve the problem; and

validating and assessing the proposed approach, using real case studies.

The next chapter presents the methodology undertaken throughout the present study.

Chapter 3

Methodology

Summary: This chapter presents the methodology undertaken in this doctoral project. In the first section, we present some methodological choices related to our new approach, integrating urban freight and the intercity passenger transport network. The following section presents the fundamental characteristics of the system operation, focusing on the physical, information and financial flows. Finally, in the last section, we present and discuss some methodological aspects that are specific to the case study.

3.1. Methodological choices

The methodological approach designed for this dissertation assumes we have access to a network with multiple customers, vehicles, and flows (cargo and passengers). It is important to highlight that the purpose of this work is just to develop a general and conceptual framework around an idea for a business model. Many specific information and a set of details (as pricing, handling times, specific goods to be moved, etc.) were not taken into account in this approach (they can be timely approached in future research works). However, in terms of the idea operationalization, a Decision Support System (DSS) should be designed, to be integrated with the internet, and allowing the users to feed the system with real and on line information.

For modeling purposes, we will take into account the following aspects.

Business model: a summary description showing how the integration between urban freight and passengers transport will be performed and operationalized. To detail the business model, the following features have to be considered:

- *Customers requirements* (such as goods and people mobility demands) and the generated benefits (cost reductions due to transport convenience, traffic and congestion decrease, reduction of noise, visual and environmental pollution).
- *Infrastructure description* (transports and equipment): distribution centers, storage areas at bus stations, handling machine types and cargo unitization tools.
- *New business models related issues,* such as employment and income generation.

Data Collection: data collected from different agents will be needed to accomplish the proposed goals. This data will be divided into three groups, as follows:

- *Passengers transport offer* (origin and destination points, time windows, transport modes available, vehicles routes, cities visited) – this kind of data can be collected by consulting transport companies (e.g. through websites) as well as regulatory agencies.
- *Urban freight* (transport demand) – this information can be obtained by the enterprises that will need the service (retailers and wholesalers, in general). Here, in principle, we will consider supermarkets and suppliers, and the types and specifications of products will comply to some pre-defined rules (products cannot have risk characteristics, and must allow standard unitization by pallets, or fragmented if they have a packing that provides the correct protection).
- *Vehicles* (available space at luggage compartments and weight specifications) – this information can be obtained from transport companies, and average numbers will be estimated and used.

Model parameters: Information that will be used as model input. In this context, each network agent will have a different role:

- *Transport companies* – will provide information on the trips in progress. The available space at the vehicles luggage racks can be estimated by a stochastic simulation model or by considering worst possible cases.
- *Goods suppliers and clients* – will provide information on the number of goods to be moved from a given point to another point.
- *Terminals* – will manage the system by allocating the goods to the network flows, according to recommendations of the developed model.

Modeling: A mathematical model will generate an optimized and coordinated integration of the cargo transport needs with the passenger vehicle available space (this model represents the business model). The following approaches were developed in our work, to help solving the problem:

- *Mixed and integer programming* – will be used to find the allocation flows that minimize total network costs and times, respecting a set of pre-determined constraints, such as vehicle capacities and available flows; these approaches should take into account the requirements and perspectives of the different system actors and stakeholders.

- *Heuristics and metaheuristics* – these techniques will probably be used to efficiently produce satisfactory solutions, as the problems under study are NP-hard.

3.2. Fundamental characteristics of the system

The city logistics system to be developed in this project will have its operation guided by the following flows: materials, information, and finances. These system features are briefly presented in the next sections.

In what concerns information flows, they will feed a planning process that will be based on a Decision Support System (DSS) where the algorithms to be developed will be embedded.

3.2.1. Physical flows

1. the cargo is packed, palletized (or not, depending on the requirements) and taken to the bus station warehouse by the supplier;
2. unloading is done at the source terminal dock, in which the cargo is briefly checked (without opening or breaking the package);
3. the cargo is duly labeled and handled by specific equipment into storage zone 1;
4. when transport is available, the cargo is removed from the permanent storage area and taken to the dock;
5. a brief checking process is carried out;
6. vehicle freight loading is performed after passengers have entered the vehicle;
7. if the vehicle capacity is not sufficient, the cargo is taken back to the warehouse, to wait for another transport allocation;
8. the cargo is transported in the vehicle to the destination terminal;
9. when the vehicle reaches the destination, the cargo is unloaded and undergoes a brief checking and separation;
10. if this warehouse is not the final cargo destination, it goes to storage area 1, and the cycle is repeated from *point 4.* above; otherwise, the cargo goes to storage zone 2;
11. the customer is notified, to pick up his goods from storage zone 2.

3.2.2. Information flows

1. the supplier feeds the DSS with information concerning the cargo to be dispatched;
2. the supplier provides the cargo destination;
3. the payment method is selected;
4. the DSS generates the routine flow (a document) that defines the flows from the origin to the final destination (the routine flow will be available to all system users, namely, the supplier, the client, and the warehouses involved);

5. tax and shipment documents are taken to the source warehouse attached to the cargo;
6. the source warehouse notifies the system about the arrival of the cargo to the stock (each supplier has only access to information about his cargo);
7. the source warehouse produces a freight label (according to the destination);
8. the source warehouse notifies the system when the vehicle takes the cargo to the next warehouse (the destination warehouse receives this notification);
9. the destination warehouse acknowledges the cargo arrival;
10. if this warehouse is not the final cargo destination, go to *point 4.* above; otherwise, a notification is issued on the goods arrival;
11. the system is notified that the goods were delivered to the customer.

3.2.3. Financial flows

1. at the moment of the routine flow (document) generation, the price of the service is computed;
2. the supplier makes the payment, according to one selected payment option;
3. according to the routine flow, the "value" provided by each part (warehouses involved and transport companies) is computed;
4. the associated money transfers are made.

The flowchart in Figure 4 summarizes the different flows in the network operation.

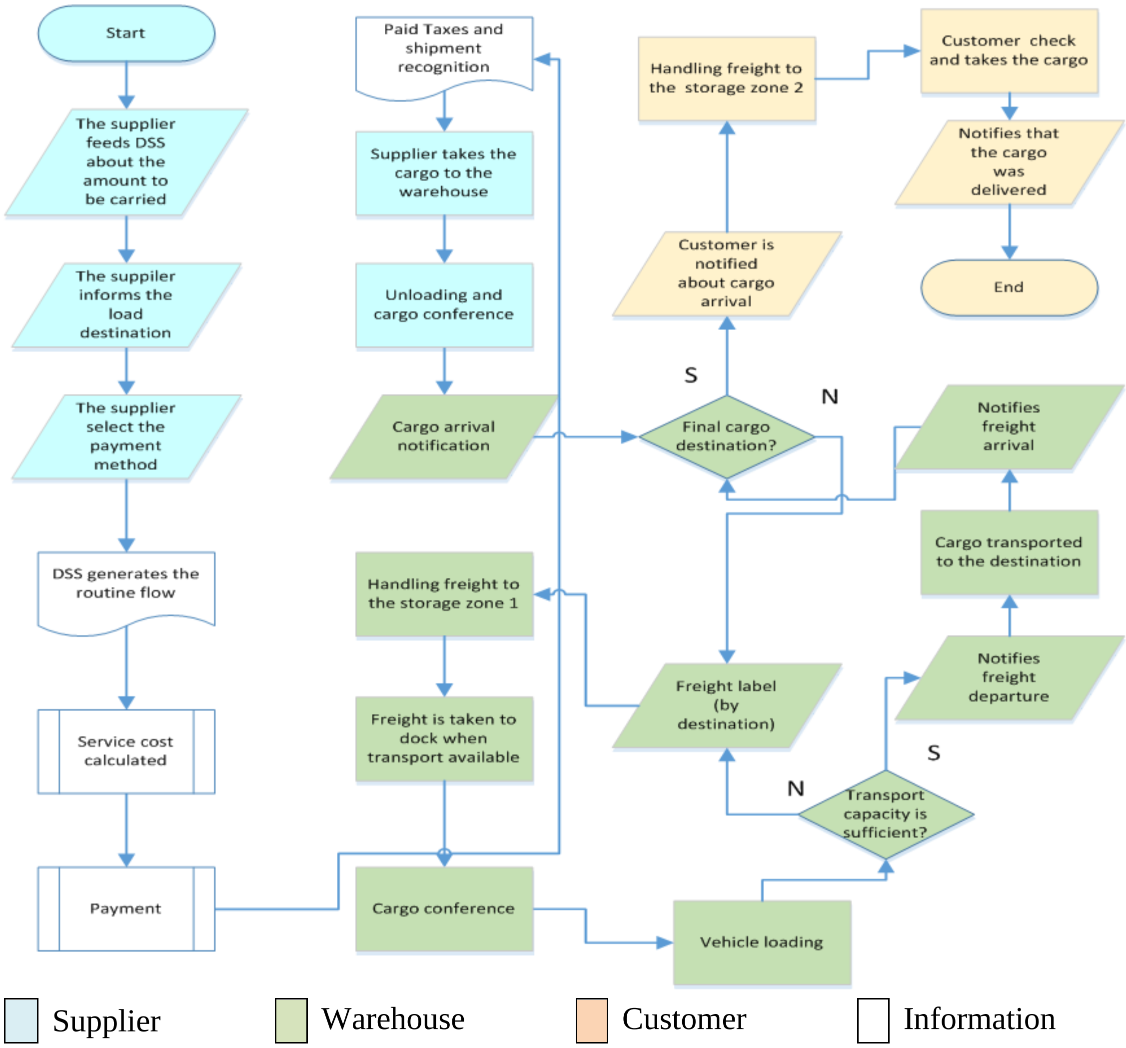


Figure 4 – Fundamental flows of the system

3.3. The methodology in the case study

For validation and assessment purposes, this approach was applied to a case study defined around the intercity road passenger's transport system in the state of Ceará, Brazil.

In this context, the system was modeled as a graph, with the nodes representing the bus stations in the cities, and the sets of arcs being the transport lines. As referred, the goods to be transported will be supermarket products (which do not have any risk characteristics, such as perishability, the tendency to explode, fragility, refrigeration requirements), textile products, shoes, technological accessories, or others.

One aspect that makes the system rather attractive to the users (supplier and customer) is sharing transportation resources. In other words, the vehicles will follow their route, regardless of whether there is cargo allocated or not. The allocation of cargo into the vehicles will not generate significant additional costs for the transport companies. Therefore, although no effort was made to price the service in the present study, we believe that the cost of using the service will be low, thus allowing it to be made available at a very competitive price.

Finally, to characterize the test instances as close as possible to reality, transport system data was used to support a random generation of the demand values. One of the main objectives of using this case study is, therefore, to find out if the proposed model can be used in practice to allocate a given demand of cargo to the transportation lines. The case study was also used to check the validity and performance of the system that was developed in the framework of this research project.

The next chapter presents the general lines of the multi-commodity network flow problem with multi-transport lines, multiple vehicles, and time windows.

Chapter 4

Multi-commodity network flow problem with multi-transport lines, multiple vehicles, and time windows

Summary: This chapter describes a modeling approach for the problem under study. In the first section some aspects related to the model building process are discussed, exploring the similarity and differences between our approach and the traditional multi-commodity network flow problem. The second section presents a mathematical model of the multi-commodity network flow problem with multi-transport-lines, multiple vehicles, and time windows. Finally, a problem representation is proposed, aiming to provide a better understanding and structuring of the problem.

4.1. Model building

As previously referred, the problem consists in delivering a group of goods (cargo), from different suppliers to a group of customers, through a passenger transport network with limited capacity. The network will be composed by a set of nodes, representing the passenger terminals, which will be used to temporarily store the goods (products), and by a set of arcs, representing a set of bus lines paths.

Therefore, the problem can be structured by considering an alternative product distribution network, to represent passenger transport freight flows occurring in parallel with traditional transport lines. The approach proposed in this work consists in transporting the goods in the existing passenger lines, using the empty spaces in the vehicle baggage racks, and we believe that this will hopefully lead to an additional convenient transport mode, resulting in lower costs, traffic, and pollution, and, if properly managed, in better service times.

We have initially developed our model based on two well-known related problems from the literature: the multi-commodity network flow problem, and the fixed charge network flow problem. The multi-commodity network flow problem consists in distributing different types of products in a network, with limited vehicle capacities, aiming to reduce the total distribution costs, that vary according to the distance (Kennington, 1978). Moreover, the fixed-charge network flow problem consists in distributing a product in a network with limited capacities, aiming to minimize the distance (variable) costs and the structural (fixed) costs (Kim & Hooker, 2002).

Given its nature, a much better understanding of the problem can be achieved through an adequate graphic representation. In such a graph, vertices represent the bus stations, and arcs represent the transport lines. There is a fixed cost associated with the used infrastructure and vehicles (i.e., station space and transport) and a variable cost that varies with the traveled distance.

By now, several representative test instances have already been run with the CPLEX optimization solver, version 12.6.1: at a first stage, small instances were used, and later, larger instances were tested, as a way to validate the models (concerning their adherence to reality) and to check the quality of results. Good, promising computational times were obtained in this phase. Moreover, these tests were also a way to identify new interesting problem characteristics that helped us in modifying and enhancing the model, as described in what follows.

To adequately handle the problem, we need to take into account the timetables and schedules of the different urban transport lines. Therefore, variables to represent the time deliveries dimension have been considered. The initial idea was that these variables would limit the timing for the delivery of the goods, and establish a customer bonus (i.e., a penalization cost for the system), defined according to the cargo volume and the days of delay. However, due to the difficulty in considering this issue in practical terms, a simplification was adopted. First, due to the operational nature of this problem, we will consider a planning horizon of only one day. Second, for each arc and each day, the flow is bounded by the capacity of all vehicles that run along that arc in that day.

Moreover, the adoption of variables for the fixed charges turned out not to be very realistic. In practice, the fixed costs associated with the used infrastructure and vehicles would be better represented if also considered as variable costs. This practical observation resulted from understanding that financial flows could be managed more easily if all costs were considered to be paid by the users, according to the total transported amounts, with the above "fixed costs" diluted in this total value.

Another modeling option was to group the network arcs into transport lines. So, the data structures for the capacity of the vehicle do not directly consider the arc capacity, but rather the transport line capacity associated with that specific set of arcs. In this way, we were able to extend the model for considering that the freight can be loaded and unloaded in intermediary nodes.

The consideration of transshipment in the network nodes and the transport lines time windows suggests the possibility of another objective function, related to time optimization. The time and cost can be conflicting in some situations (where the transshipment compensates in terms of cost but not in terms of time, for example), this justifying considering both aspects simultaneously.

4.2. Mathematical model

In general terms, this problem can be represented by the following mathematical model, that can be viewed as a multi-objective multi-commodity network flow problem with multiple transport lines.

In this approach, the extensions of the original model are performed through a graph $G = (V, E)$, that accommodates the following problem features.

Each edge E has:

- a variable cost related to the specific transported product amount;
- a lower bound for volume per freight;
- an upper bound for volume per freight.
- a departure time related to each vehicle from the transport line;
- a travel duration related to each vehicle from the transport line;
- an arrive time related to each vehicle from the transport line.

Each vertex V has:

- an offer/demand freight value related to each kind of product.

The sets of entities considered in the model are as follows:

- G: suppliers (representing the different types of products);
- D: circuit demand nodes;
- E: circuit edges;
- V: circuit vertices;
- C: a total transport capacity by vehicle;
- L: transport lines.
- T: vehicles in transport lines.

Parameters:

- $c_{tovqkij}$: unit variable cost for arc (i,j) and each product from product k and transport line t, vehicle v to transport line o, vehicle q;
- a_{ijt}: the capacity of arc (i,j) and transport line t (total daily transport line cargo capacity);

- b_{ik}: demand from node *i* by product *k*;
- $l_{tovqkij}$: lower bound for the flow from the arc (*i*,*j*) to product *k* and from transport line *t*, vehicle *v* to transport line *o*, vehicle *q*;
- $u_{tovqkij}$: upper bound for the flow from the arc (*i*,*j*) to product *k* and from transport line *t*, vehicle *v* to transport line *o*, vehicle *q*.
- $p_{tovqkij}$: departure time for arc (*i*,*j*) and each product from product *k* and transport line *t*, vehicle *v* to transport line *o*, vehicle *q*;
- $h_{tovqkij}$: duration time for arc (*i*,*j*) and each product from product *k* and from transport line *t*, vehicle *v* to transport line *o*, vehicle *q*;
- $d_{tovqkij}$: arrive time for arc (*i*,*j*) and each product from product *k* and from transport line *t*, vehicle *v* to transport line *o*, vehicle *q*;

Decision variables:

- $y_{tovqkij}$: flow from the arc (*i*,*j*), of the product *k* and from transport line *t* , vehicle *v* to transport line *o*, vehicle *q*.
- $x_{tovqkij}$: indicates whether the arc (*i*,*j*), of the product *k* and from transport line *t*, vehicle *v* to transport line *o*, vehicle *q* was used.
- $w_{tovqkij}$: indicates the total displacement time of the freight along an arc (*i*,*j*), of the product *k* and from transport line *t* , vehicle *v* to transport line *o*, vehicle *q*.

Model:

$$\min \sum_{(t,o,v,q,k,i,j)\in E} c_{tovqkij}\, y_{tovqkij} \qquad (1)$$

$$\min \sum_{(t,o,v,q,k,i,j)\in E} w_{tovqkij} \qquad (2)$$

subject to:

$$\sum_{j:(t,o,v,q,k,i,j)\in E} y_{tovqkij} - \sum_{j:(t,o,v,q,k,i,j)\in E} y_{tovqkji} = b_{ik}\ , \forall\ i,k\ \in V \qquad (3)$$

$$\sum_{j:(t,o,v,q,k,i,j)\in E} y_{tovqkij} \le a_{oqij}\ , \forall\ (o,q,i,j) \in E \qquad (4)$$

$$l_{tovqkij} \le y_{tovqkij} \le u_{tovqkij}\ , \forall\ (t,o,v,q,k,i,j) \in E \qquad (5)$$

$$y_{tovqkij} \le \left(\sum_{(i,k)\in V, \forall\ b>0} b_{ik} \right) x_{tovqkij}\ , \forall\ (t,o,v,q,k,i,j)\ \in E \qquad (6)$$

$$x_{tovqkij} \le y_{tovqkij}\ , \forall\ (t,o,v,q,k,i,j) \in E \qquad (7)$$

$$x_{tovqkij} \times d_{tovqkij} \le w_{tovqkij}\ , \forall\ (t,o,v,q,k,i,j) \in E \qquad (8)$$

$$y_{tovqkij} \le 0\ , \forall\ (t,o,v,q,k,i,j) \in E \qquad (9)$$

$$w_{tovqkij} \leq 0 \text{ , } \forall \; (t, o, v, q, k, i, j) \in E \tag{10}$$

$$x_{tovqkij} \in \{0,1\} \text{ , } \forall \; (t, o, v, q, k, i, j) \in E \tag{11}$$

Pre-processing conditions:

$$w_{tovqkij} = p_{tovqkij} + h_{tovqkij} \text{ , } \forall \; (t, o, v, q, k, i, j) \in E \tag{12}$$

$$a_{oqij} < \sum_{(t,o,v,q,k,i,j) \in E} \left(u_{tovqkij} - l_{tovqkij}\right) \text{ , } \forall \; (o, q, i, j) \in E \tag{13}$$

$$\sum_{(i,k) \in V} b_{ik} = 0 \tag{14}$$

Objective function (1) represents the network operational costs, while objective function (2) represents the travel times, both to be minimized. The set of equations (3) guarantees the flow conservation on the vertices. Equations (4) guarantee that the flow in the arc does not exceed its total capacity. Equations (5) define the upper and lower bounds on the arc flows. The set (6) guarantees the inexistence of flow in arcs where vehicle time windows are incompatible while the set (7) secures that the binary variable will assume the value "one" just when the arc is being used. The equations set (8) secures the time compatibility between vehicles from different transport lines. Equations (9) and (10) ensure the non-negativeness of the flow and time variables, respectively. Expressions (11) define the time compatibility for each vehicle. Finally, the next three sets of equations are pre-processing conditions. The equations set (12) defines the time spent in the arcs. Equations (13) consider the vehicle's capacities for each arc, and equations (14) guarantee that the total offer will be sufficient to satisfy all the demand.

We have defined three data structures for the problem parameters. The first is called "*Edges*,". An "edge" represents the link between nodes given by each vehicle moving each product. The following expression will give the *Edges* number:

$$Edges = \left[\sum_{i=1}^{t} (arc_i \times v_i) \times k\right] + \left[\sum_{i=1}^{t} \left(arc_i \times dest_j \times {v^2}_i\right) \times k\right], \forall \; j \in D$$

where:

- *t:* the number of transport lines;
- *arc:* the number of arcs of each transport line;
- *k:* the number of products;
- *v:* the number of vehicles in each transport line;
- *dest:* the number of destinations to different transport lines of each arc;
- *D:* the total number total of destinations from each net arc.

The second data structure is called “*Capacities*” and is used to store the value related to the capacity of each vehicle from the transport lines in each arc. The expression to define its value is given by:

$$Capacities = \sum_{i=1}^{t} arc_i \times v_i$$

where:

- *t:* the number of transport lines;
- *arc:* the number of arcs of each transport line;
- *v:* the number of vehicles in each transport line;

The third data structure is called “*Vertex*” and stores the values related to network offer and demand for products. Negative values will represent product offer, and the positive ones represent demand. The expression to define the value of *Vertex* is given by:

$$Vertex = \sum_{i=1}^{k} nodes_i$$

where:

- *k:* number of products;
- *nodes:* a binary variable

After the definition of these structures, it is possible to estimate the "dimensions" of the model:

- decision variables type *y*, *w*, and *x*, equal to *Edges* number;
- constraints of type (3) and (14) equal the number of *Vertex*;
- constraints type (4) and (13) equal the number of *Capacities*;
- constraints type (5), (6), (7), (8), (9), (10), (11) and (12) equal the number of *Edges.*

We are here using the following indices and associated element sets:

indices	*sets*
k	*G*
i	*V* (origin nodes)
j	*V* (destination nodes)
t	*L* (origin transport lines)
o	*L* (destination transport lines)
v	*T* (origin vehicles)
q	*T* (destination vehicles)

4.3. Problem representation

Aiming to perform a first assessment of this mathematical model, we have generated a random and small instance, with a structure similar to the real world problem. Such preliminary assessment was performed with the IBM ILOG CPLEX software, version 12.6.1 with the main purpose of validating the model and checking whether there were bugs or inconsistencies. This instance was run in a CPU Intel Core i7-4710 HQ 3.5 GHz and 8GB memory.

To explain the approach and illustrate how the model works, a small example is now provided, along with its graphical representation.

Consider a set of 6 cities, forming a network. There are two kinds of *k* products to be delivered (and moved between the cities) by 4 transport lines with 2 vehicles each. The network can be represented (with the above notation) by the following graph $G = (V, E)$ – see Figure 5 below, with:

$V = (b_{i1}, b_{i2})$

where:

- *b*, when positive represents the product offer, and when negative represents product demand; and

$E= (a_{ijtv} ; u_{tovqijk}; l_{tovqijk}; c_{tovqijk}; h_{tovqjik})$

where:

- *a* represents vehicle *v* capacities from each line *t* to each arc (*i*,*j*);
- *u* and *l* represent the upper and lower limit (respectively) of product *k* that can be allocated to each vehicle *v* (origin) and *q* (destination), from transport line *t* (origin) and o (destination) in each arc (*i*, *j*);
- *c* represents the cost related to the freight of product *k* that can be allocated to each vehicle *v* (origin) and *q* (destination), from transport line *t* (origin) and o (destination) in each arc (*i*, *j*);
- *h* represents the travel duration time of product *k* that can be allocated to each vehicle *v* (origin) and *q* (destination), from transport line *t* (origin) and o (destination) in each arc (*i*, *j*);.

The "relative" departure times (*ptovqjik*) of the transport lines’ first vehicle are:

transport line	*departure time*
1	0
2	2
3	1
4	3

The second vehicle of each transport line departs two hours after the first one. The arrival time (*dtovqjik*) of the vehicle in node j will be the departure time from node i plus the duration time (*htovqjik*) of the arc (*i,j*). Figure 5 presents a random problem instance to illustrate the used problem representation.

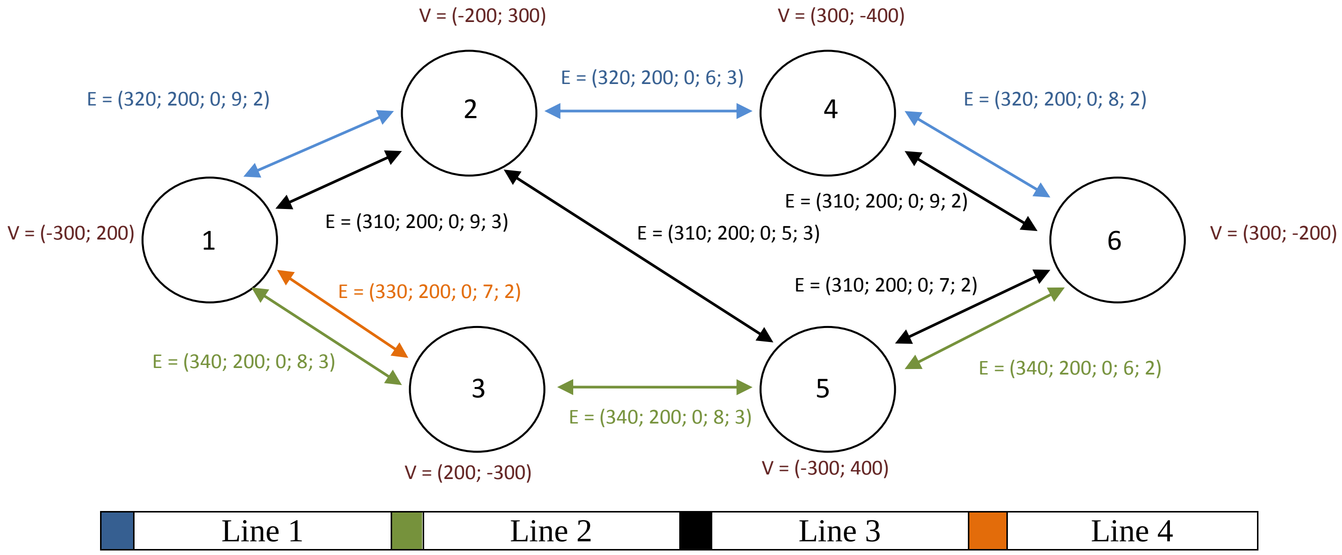


Figure 5 – Random problem instance

Figure 6 presents the solution obtained by the model for the cost objective function. The value on each arc is the amount (cargo) transported between each pair of vertices (all the network demand is satisfied with this solution). The total cost (objective function value) is Z = 12,200 (monetary units), with an execution time of 0,01 seconds.

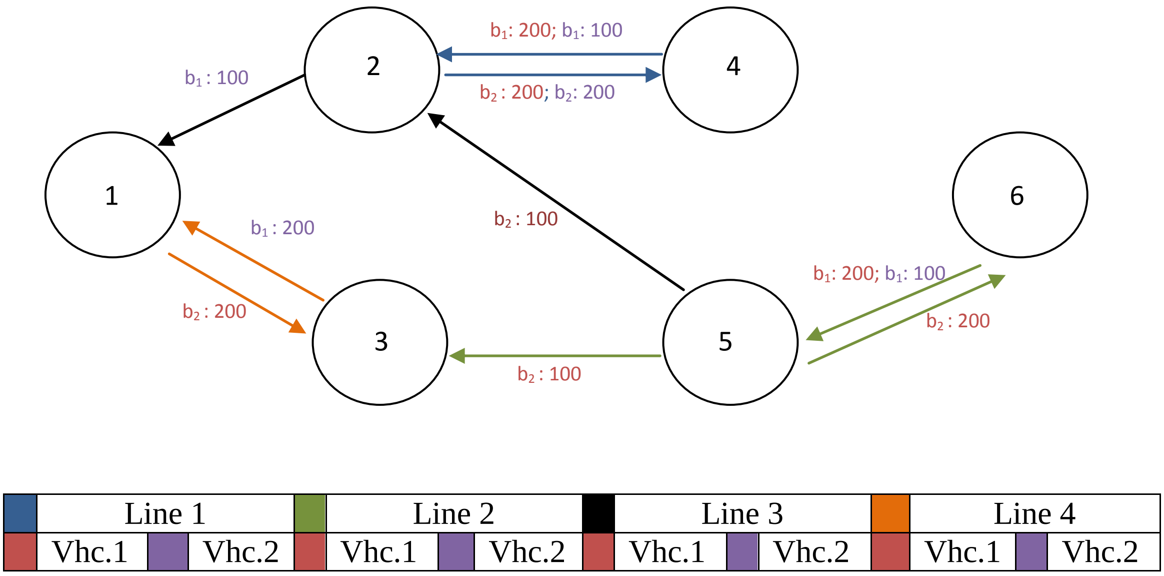
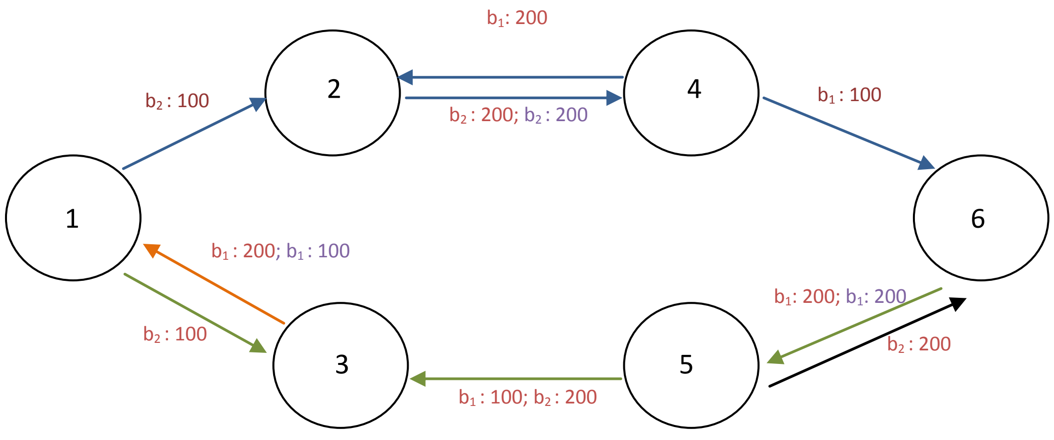


Figure 6 – Problem solution to the cost objective function

Figure 7 presents the solution obtained by the model to the time objective function. As in the previous case, the value on each arc is the amount (cargo) transported between each pair of vertices (all the network demand is satisfied with this solution). The total time (objective function value) is $Z = 101$ (hours) and with an execution time of 0,02 seconds.



	Line 1				Line 2				Line 3				Line 4		
	Vhc.1		Vhc.2		Vhc.1		Vhc.2		Vhc.1		Vhc.2		Vhc.1		Vhc.2

Figure 7 – Problem solution for the time objective function

The solutions are "consistent" as all customers were served with the network minimal cost/time. We can also see that the time-based approach tends to minimize the total amount of transshipments as it tends to increase the travel times. However, we should note that the approach is based on a simplified model, and some refinements must be performed yet.

The next chapter presents the solution approach methods developed to solve the multi-commodity network flow problem with multi-transport lines, multiple vehicles, and time windows.

Chapter 5

Resolution Approach

Summary: In this chapter we describe two heuristic algorithms developed to solve the multi-commodity network flow problem with time windows, multi-transport lines and multiple vehicles. We also present a methodology that was designed to integrate the heuristics with the mathematical programming models (via CPLEX), thus establishing four solution methods. The approaches were implemented using the C++ language, and the optimization model was implemented and solved using the *concert* technology and IBM ILOG CPLEX optimization environment, version 12.6.1.

Two heuristic algorithms were developed to solve the multi-commodity network flow problem with time windows, multi-transport lines and multiple vehicles. The first step of both heuristics is to read a data structure composed by tree matrices: edges, capacity, and vertex. It is important here to present some details of this data structure in order to help explaining the operation of the heuristics.

The *edges* structure contains information related to 13 attributes: origin transport line (*t*); destiny transport line (*o*); origin vehicle (*v*); destination vehicle (*q*); commodity (*k*); origin node (*i*); destination node (*j*); cost (*c*); upper capacity bound (*u*); lower capacity bound (*l*); departure time (*p*); travel duration (*h*); and arrival time (*d*). All the possibilities of movements will be represented by additional edges (as it is also the case of transshipments).

The *capacity* structure stores the information related to 5 attributes: destination transport line (*o*); destination vehicle (*q*); origin node (*i*); destination node (*j*); capacity (*a*). It should be noted that the capacities are shared among the commodities, so that (*a*) represents the total amount of cargo to be transported by the vehicle, while (*u*), in the edges structure, represents the total of each commodity to be transported in that arc.

Finally, the *vertex* structure, stores 3 attributes: commodity (k); node (i); offer / demand (*b*). The offer and demand nodes have different signs: negative means demand, and positive means offer.

In the next sections the heuristics developed in this work are described, namely the "Size Reduction" heuristic, the "LP-and-fix" heuristic, and a hybrid algorithm that combines the two previous heuristic approaches.

5.1. Size reduction heuristic

According to Fanjul-Peyro and Ruiz (2011), a reduction heuristic explores the topology of the problem and reduces some problem attributes without making its solution infeasible. The authors obtained good results applying a set of metaheuristics based on a size-reduction of the original assignment in the unrelated parallel machines scheduling problem. The method produced solutions of very good quality, in a short amount of time.

The reduction heuristic described here has a very simple operating mechanism. As presented in Chapter 3, the number of possible edges significantly increases the complexity of the data structure. Therefore, the size reduction heuristic will reduce the number of edges, as a way to reduce the number of available options to move the goods along the transport network.

This procedure can in some way, worsen the value of the solution, depending on the reduction size (given by a reduction percentage), but it is expected that it also reduces the computational times obtained, this being the objective.

Therefore, the developed approach makes reductions analyzing the pairs of origin (*i*) / destination (*j*) nodes that are repeated throughout the data structure. In this way, the procedure does not impair the functioning of the network. The number of nodes analyzed by the algorithm will depend on the given reduction percentage.

The reduction criteria are based on first analyzing the cost and then the time. The algorithm traverses all the edges of the network and creates a list containing the edges with repeated pairs (*i, j*) of origin and destination nodes, so that the edges in the list are ordered decreasingly in terms of costs and time. The reductions are made using the given reduction percentage, starting with the edges in the top of the list.

It should be noted that the edge reductions in the heuristic procedure need to be made in a rather smart way, as the multi-transport line with transshipment possibilities increases a lot the complexity of the problem. This is due to the increase in the number of choices to move goods between the origin and destination nodes, as each edge is a new possibility to make the freight, between the same nodes but using different transport lines, vehicles and with or without transshipment.

For instance, we can have various ways to move the same cargo from a given node *i* to another node *j*, e.g., using different transport lines with different vehicles, costs, capacities, time windows, and making or not a transshipment between two transport lines. I.e., each new edge represents a new possibility for this choice.

Therefore, the size reduction heuristic algorithm will list all the origin and destination nodes that are repeated (creating a list of repetitions that stores the edges positions in the matrix edges) over the network, and eliminating from the data structure (specifically from the edges matrix), those that have the largest costs and times. Thus, the chances of making the network operation unfeasible through reductions of its edges decreases. In this way, the procedure allows larger reduction percentages without making the problem unfeasible.

At this time, it should be noted that in the repetitions list we are only considering the repetition of the origin and the destination nodes inside the matrix edges structure (which has 13 indexes), all other elements of the various listed edges being different themselves.

The pseudocode of the size reduction algorithm is presented in Figure 8.

```
begin
INPUT generated_instance;

            reading_data()    / /carries out the data structure
            INPUT generated_instance;
                 repeat
                      read each element of data structure edges and store in the matrix_edges[ ][ ];
                      read each element of data structure capacity and store in the matrix_capacity[ ][ ];
                      read each element of data structure vertex and store in the matrix_vertex[ ][ ];
                  until all the data has been read;
            OUTPUT matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];

       repeated_edges()       //creates a list with repeated edges
            INPUT matrix_edges[ ][ ];
                 repeat
                      search repeated pair of origin (i) and destination (j) nodes in matrix_edges[ ];
                      creates the vector repeated_list[ ];
                      stores the repeated nodes position in repeated_list[ ];
                 until all the repeated nodes position be included in  repeated_list [];
             OUTPUT repeated list[ ];

       ordering_positions();        // ordering decreasingly repeated_list in terms of cost and time
            INPUT repeated_list[ ], matrix_edges[ ][ ];
                  read each element of repeated_list[ ];
                 repeat
                      order decreasingly each element of the repeated_list[ ] according with correspondent
cost (c) in matrix_edges[ ][ ];
                      order decreasingly each element of the repeated_list[ ] according with correspondent
time (p) + (h) in matrix_edges[ ][ ];
                 until all the repeated_list[ ] values has been ordered in terms of cost and time;
            OUTPUT repeated_list[ ]; //ordered

       reduction_positions()        //eliminates positions in the matrix_edges[ ][ ] according to
informed percent
            INPUT matrix_edges[ ][ ], repeated_list[ ], reduction_percent;
                 repeat
                      eliminates the position in the top of restricted_list[ ] in matrix_edges[ ][ ];
                 until performs the reduction percent;
            OUTPUT matrix_edges[ ][ ];    //reduced

       concert_CPLEX_solve()
            INPUT matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];
                 solve the problem using CPLEX optimization environment through concert technology;
            OUTPUT total_solution_value, computational_time, solution_gap;
end
```

Figure 8 – Size reduction heuristic

5.2. LP-and-fix heuristic

According to Toledo, (2015), heuristics based on mathematical programming are an efficient way to solve mixed integer problems. The relaxation and fixation heuristic described in this section has, as the above procedure, a very simple operating mechanism. It consists in relaxing some integer or binary decision variables, (easily) solving the relaxed model, then fix the values of those variables according to some rule or criterion and finally, solving the resultant problem.

In our problem context, the LP-and-fix heuristic was implemented relaxing the value of the binary decision variables “x” (that indicate the presence or not of a flow in a given edge) letting them have values between “0” and “1”, and then solving the problem in these conditions using the CPLEX optimization environment. After that, the algorithm fixes the values of variables with a 0 value to 0, and those with a 1 value to 1, and then solves the resultant problem using the same optimization tool.

This relaxed problem is easily solved, as it has more freedom of choice in terms of allocation levels between the network edges. Then, by fixing the variables to “0” or “1”, we significantly reduce the search procedure, making the optimization easier.

The two other sets of decision variables, “y” (the amount of goods moved in each edge) and “w” (the amount of time spent by each edge) are already continuous variables.

The pseudocode of the LP-and-fix algorithm is presented in the Figure 9.

```
begin
INPUT generated_instance;

        reading_data()    / /carries out the data structure
        INPUT generated_instance;
            repeat
                read each element of data structure edges and store in the matrix_edges[ ][ ];
                read each element of data structure capacity and store in the matrix_capacity[ ][ ];
                read each element of data structure vertex and store in the matrix_vertex[ ][ ];
            until all the data has been read;
        OUTPUT matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];

    relaxing _x[ ]()        //relax binary variable with values between 0 and 1
        INPUT matrix_edges[ ][ ];
            creates the vector x[ ] with the same number of matrix_edges[ ][ ] positions;
            repeat
                relax all the positions of the vector x[ ] with values from 0 until 1;
            until all the positions has been relaxed;
        OUTPUT x[ ];    //relaxed values

    concert_CPLEX_solve()        //solve relaxed problem
        INPUT x[ ],matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];
            solve the problem using CPLEX optimization environment through concert technology;
        OUTPUT total_solution_value, computational_time, solution_gap, x[ ];

    fixing _x[ ]()            //fix the values of the binary variable with 0 or 1
        INPUT x[ ];
            repeat
                read the values of each position of vector x[ ];
                fix the position of the vector x[ ] with values 0, as 0 and 1, as 1;
            until all the positions has been fixed;
        OUTPUT x[ ];    //fixed values

    concert_CPLEX_solve()
        INPUT x[ ],matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];
            solve the problem using CPLEX optimization environment through concert technology;
        OUTPUT total_solution_value, computational_time, solution_gap;

end
```

5.3. Hybrid Algorithm: Combining the Size Reduction and the LP-and-fix

A third approach was developed to solve the multi-commodity network flow problem with time windows and multiple transport lines. It is an algorithm that hybridizes the Size Reduction heuristic and the LP-and-fix for solving the proposed problem.

In a simple way, this approach consists in first reducing the number of arcs by a pre-established percentage from the matrix “edges” (in the tests of this work we have used 20% of reduction), as described in Section 5.1.

Then, the algorithm will take into consideration the matrix edges obtained by the previous step, jointly with other data structures (capacity and vertex) and apply the LP-and-fix methodology to solve the problem with the relaxed binary decision variables "x". Afterwards, the value of these variables are fixed to "1" or "0", according to a pre-established criterion (see above), and the problem is solved again (as described in section 5.2 above).

All the steps of the approached are supported by the CPLEX software, i.e., the algorithm is developed using the C++ language and its interface with CPLEX is made using the *Concert* technology.

The pseudocode of the hybrid algorithm is presented in Figure 10.

```
begin
INPUT generated_instance;

        reading_data()    / /carries out the data structure
        INPUT generated_instance;
            repeat
                read each element of data structure edges and store in the matrix_edges[ ][ ];
                read each element of data structure capacity and store in the matrix_capacity[ ][ ];
                read each element of data structure vertex and store in the matrix_vertex[ ][ ];
            until all the data has been read;
        OUTPUT matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];

    size_reduction()       //applies the size reduction method
        INPUT matrix_edges[ ][ ], reduction_percent;
            repeat
                reduce the nodes in matrix_edges[ ][ ];
            until all the nodes be reduced according to reduction_percent;
        OUTPUT matrix_edges[ ][ ];

    lp_and_fix()       //applies the LP-and-fix method
        INPUT matrix_edges[ ][ ], matrix_capacity[ ][ ], matrix_vertex[ ][ ];
            relax all the positions of the vector x[ ] with values from 0 until 1;
            solve the problem using CPLEX optimization environment through concert technology;
            fix the position of the vector x[ ] with values 0, as 0 and 1, as 1;
            solve the problem using CPLEX optimization environment through concert technology;
        OUTPUT total_solution_value, computational_time, solution_gap;

end
```

Figure 10 – Hybrid algorithm

5.4. Resolution Methods

The generated test problem instances were run in the CPLEX optimization IDE using the *Concert* technology and the Visual C++ IDE, where the heuristics were implemented. This was made to analyze the performance of the tool in processing the two objective functions (related to cost and time) individually.

The solution approach was divided in four methods, as follows:

- *1st method*: this approach consists in solving the problem with MILP (mixed integer linear programming), without heuristics;
- *2nd method:* use the Size Reduction heuristic to reduce the problem size and after solve the resultant problem with MILP;
- *3rd method*: using the LP-and-fix heuristic and MILP (relax the binary variables (x), solve the resulting problem using MILP, fix the value of the variables to "0" or "1" and solve the problem again);
- *4th method*: combine the two heuristics (first the problem data structure is reduced by the Size Reduction procedure and after the problem is solved with MILP, using the LP-and-fix heuristic).

The next chapter presents the results of tests made for theoretical instances developed to evaluate the performance of the solution methods described in this chapter.

Chapter 6

Test and validation of the developed approaches

Summary: In this section were presented the results obtained by the tests made using the four methods previously described, applied to the sixty instances developed with the instances generator. In the first sub-section, the instances generator was described. In the next sub-section, the results were presented analyzed using descriptive statistical techniques and analysis of variance. Finally, in the last subsection, the results were discussed, taking into account some important considerations from the presented methods results and statistical analysis for each objective function, cost and time.

6.1. Instances generator

Three classes of instances were created in order to test the efficiency of the developed solution methods, applied to the Multi-Commodity Network Flow Problem with time windows and multiple transport lines. The problem classes vary according to the number of suppliers and nodes. For each class, it was established four variants, changing the number of nodes and suppliers. So, each class has twenty instances and there are three classes, totalizing 60 problem instances (see Table 4).

Table 4 – Instances classes

Problem Class	Class I: Small				Class II: Medium				Class III: Large				Total
Nodes	6	8	10	12	10	12	14	16	12	16	18	20	60
Suppliers	10	6	4	2	8	6	4	2	10	6	4	2	
Instances	5	5	5	5	5	5	5	5	5	5	5	5	
Total	20				20				20				

In order to better detail the generated instances features, Table 5 classifies each of the 60 instances in terms of number of nodes, suppliers, transport lines, trips and arcs.

Table 5 – Generated instances

Small Instances						Medium Instances						Large Instances					
I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI
i1	6	10	22	216	94575	i21	10	8	53	468	235740	i41	12	10	72	654	413105
i2	6	10	18	181	79980	i22	10	8	41	404	162676	i42	12	10	61	613	388705
i3	6	10	16	181	69365	i23	10	8	42	364	160488	i43	12	10	68	669	481190
i4	6	10	21	186	87060	i24	10	8	50	482	309148	i44	12	10	65	619	417300
i5	6	10	20	170	73815	i25	10	8	43	423	191508	i45	12	10	59	574	402770
i6	8	6	29	262	57663	i26	12	6	70	696	375393	i46	16	6	125	1189	511695
i7	8	6	30	299	85749	i27	12	6	64	613	266028	i47	16	6	117	1112	588696
i8	8	6	25	247	75615	i28	12	6	70	637	305202	i48	16	6	137	1242	615192
i9	8	6	32	307	96849	i29	12	6	74	761	431880	i49	16	6	131	1284	726738
i10	8	6	33	309	76293	i30	12	6	72	670	226503	i50	16	6	133	1308	816741
i11	10	4	48	438	106848	i31	14	4	97	945	307838	i51	18	4	161	1517	585702
i12	10	4	46	426	90626	i32	14	4	97	912	345654	i52	18	4	161	1518	620898
i13	10	4	46	470	88822	i33	14	4	95	897	236126	i53	18	4	164	1569	759954
i14	10	4	42	358	59834	i34	14	4	91	871	283578	i54	18	4	160	1504	453270
i15	10	4	45	435	80364	i35	14	4	90	848	195658	i55	18	4	170	1624	928826
i16	12	2	67	674	66346	i36	16	2	119	1212	263180	i56	20	2	200	1869	562159
i17	12	2	63	632	70726	i37	16	2	112	1063	192836	i57	20	2	202	1920	350582
i18	12	2	68	683	67766	i38	16	2	136	1338	269333	i58	20	2	189	1805	460345
i19	12	2	72	659	101547	i39	16	2	117	1110	179953	i59	20	2	188	1724	402777
i20	12	2	71	701	134341	i40	16	2	117	1101	203783	i60	20	2	205	1945	454412

I – Instances; II – Nodes; III – Suppliers; IV – Lines; V – Trips; VI – Arcs.

To help understanding the data presented on Table 5, some graphics were generated, showing the distribution of the data in terms of the total number of transport lines, trips and arcs for each instance generated (see Figures 11, 12, and 13).

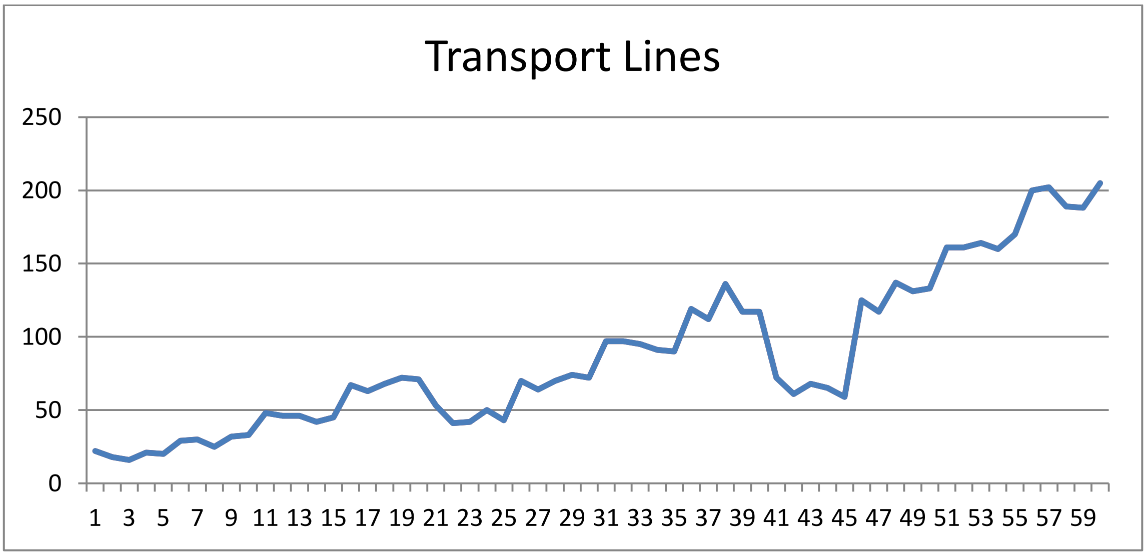


Figure 11 – Number of transport lines per instance

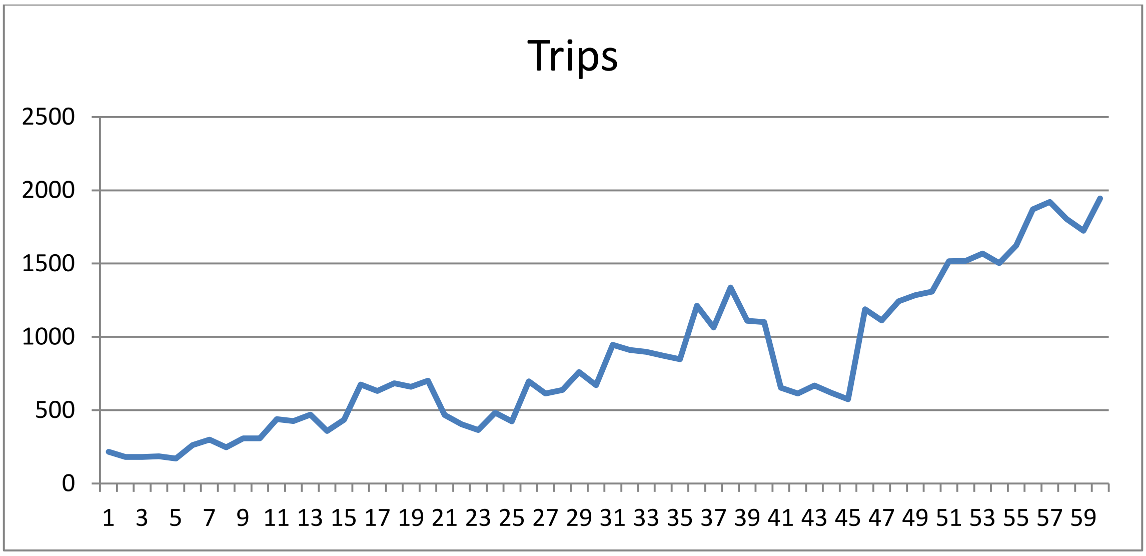


Figure 12 – Number of trips per instance

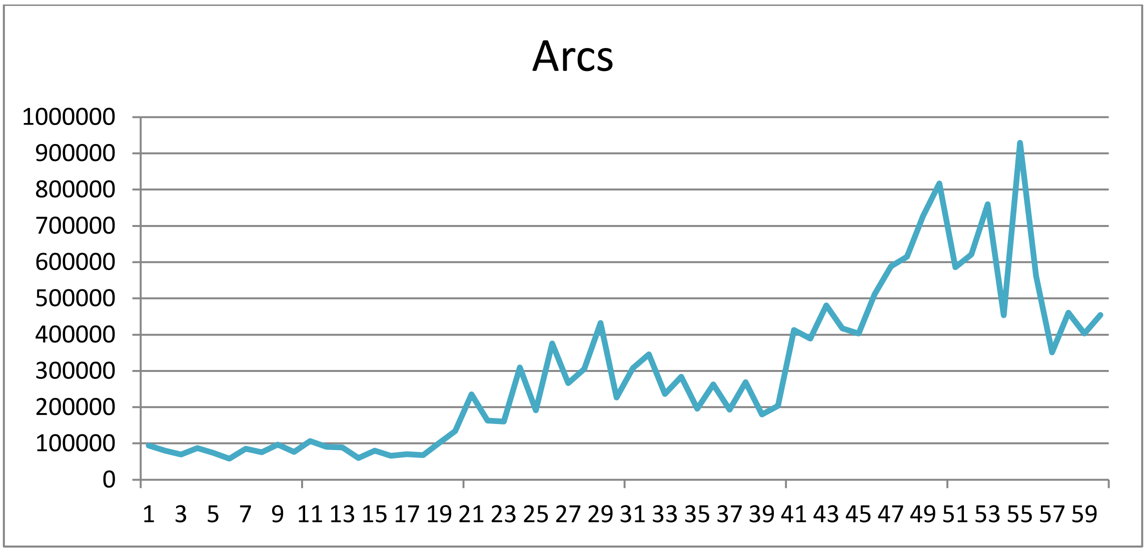


Figure 13 – Number of arcs per instance

These graphics will be useful to understand the relationships of these features with the obtained solutions (results section).

The instances were generated using an algorithm developed in C++ (on the Microsoft Visual Studio IDE) using some guidelines proposed by Alvarez et al. (2005), in order to produce feasible problems, especially considering the arcs capacity relative to the network demand. These guidelines include some rules to determine products demand by node (values between 1 and 100), arc costs (values between 1 and 100) and vehicles capacities (between 12% and 16% of the total demand of each product – however in our problem this value was defined to be between 24% and 28%, due the high number of infeasible instances under Alvarez et al. (2005) configuration).

The pseudocode of the instances generator is presented in Figure 14.

```
begin
INPUT nodes_number, products_number;
    graph()    //generates a randomized graph according to nodes_number
        INPUT nodes_number;
            repeat
                link nodes by a random way forming arcs;
            until all the nodes be linked
        OUTPUT graph;
    transport_lines();    // generates a randomized transport lines according to the graph
        INPUT graph;
            repeat
                define random sets of sequenced arcs;
                account the number of sets;
            until all the arcs be part of a sequenced set;
            define each set as a transport_line;
        OUTPUT transport_lines;
    data_structure()    //generates the problem parameters to each arc, capacity and vertex
        INPUT graph, transport lines;
            repeat
                generates demand values to each node and product;    // between 1 and 100
                generates cost values to each arc;    //between 1 and 100
                generates vehicles number to each transport line;    // between 5 and 15
                generates capacities to each vehicle of each transport line;    // 24 % to 28% of the
                total demand to each product
                generates time windows to each vehicle of each transport line;  //arrive, departure and
                travel times
            until all graph and transport line be with the proper information
        OUTPUT demand, cost, vehicles, capacities, time windows;
end
```

Figure 14 – Instances generator

In order to better analyze the efficiency of the heuristics, the "CPLEX presolve configurations" were turned off. Tests were made for the 60 instances with each of the previously described methods, and for the cost and time objective functions. Therefore, the total number of tests was $60 \times 4 \times 2 = 480$ tests.

6.2. Computational results

In this section the results obtained by the four methods applied to the two objective functions in the 60 test instances will be presented and analyzed.

6.2.1. Objective function *cost*

Results are presented in the tables below. Note that for infeasible instances, the values of the objective functions were plotted as zero.

1ST METHOD RESULTS

The results of the 1st method are presented on Table 6.

Table 6 – Results obtained with the 1st method and objective function cost

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	62909	72.14	0	i21	79087.9	333.36	0	i41	113578	1160.54	0
i2	104692	66.99	0	i22	76506.4	175.98	0	i42	188163	565.012	0
i3	98640.5	66.58	0	i23	174142	163.40	0	i43	112395	729.274	0
i4	99661	49.67	0	i24	75190.2	414.56	0	i44	0	3600	100
i5	98536.9	44.99	0	i25	75799	249.20	0	i45	146434	1563.21	0
i6	56278.9	33.96	0	i26	52530.8	833.90	0	i46	76697.3	958.745	0
i7	60721.1	168.99	0	i27	59636	272.24	0	i47	0	3600	100
i8	66149	79.98	0	i28	46136	316.32	0	i48	86256	1497.13	0
i9	71853.9	106.89	0	i29	75354.6	663.27	0	i49	70103.1	1708.39	0
i10	50599.5	52.36	0	i30	66684	327.89	0	i50	0	3600	100
i11	31248.3	3600	0	i31	38945	543.43	0	i51	27027.1	482.725	0
i12	30138.2	158.81	0	i32	44609.6	539.25	0	i52	52562	809.517	0
i13	57266.5	113.17	0	i33	39191	346.70	0	i53	0	3600	100
i14	23850.1	30.74	0	i34	57379.3	392.98	0	i54	0	3600	100
i15	33052.7	42.59	0	i35	49770	224.96	0	i55	49405.3	1298.44	0
i16	19969.8	62.54	0	i36	29526	170.91	0	i56	22635	443.165	0
i17	19969	33.24	0	i37	21690	556.63	0	i57	28822	358.248	0
i18	20862	27.18	0	i38	24173.5	233.51	0	i58	18838.6	727.76	0
i19	26974	56.48	0	i39	19925	100.12	0	i59	26604	269.944	0
i20	21207	153.96	0	i40	30715.8	119.13	0	i60	16244	521.048	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

We can observe that with the 1st method, for the majority of the instances, feasible solutions were produced. Table 7 summarizes the main information about these results.

Table 7 – Main results obtained by the 1st method

Feature	Small instances	Medium instances	Large instances
infeasible instances	none	none	i44, i47, i50, i53 and i54
instances with GAP different from zero	none	none	i44, i47, i50, i53 and i54
maximum execution time	168.99 seconds (i7)	833.9 seconds (i26)	1708.39 seconds (i49)
minimum execution time	27.18 seconds (i18)	100.12 seconds (i39)	358.24 seconds (i57)

2ND METHOD RESULTS

The results of the 2nd method are presented on Table 8.

Table 8 – Results obtained with the 2nd method and objective function cost

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	63376	56.13	0	i21	89072	262.42	0	i41	127431	1376.99	0
i2	110741	47.27	0	i22	92650	255.23	0	i42	211834	1426.23	0
i3	115888	43.34	0	i23	0	3600.00	100	i43	127397	1805.46	0
i4	108573	53.49	0	i24	91269	733.11	0	i44	0	904.94	100
i5	104548	40.31	0	i25	87096	472.84	0	i45	175140	1785.22	0
i6	63441	32.47	0	i26	0	3600.00	100	i46	84628	2339.51	0
i7	81128	68.34	0	i27	70181	600.83	0	i47	85367	3319.17	0
i8	67366	48.95	0	i28	60822	823.47	0	i48	98690	3298.01	0
i9	78748	68.74	0	i29	0	3600.00	100	i49	75716	3552.07	0
i10	60709	48.73	0	i30	0	3600.00	100	i50	0	3600.00	100
i11	46817	59.99	0	i31	43497	629.48	0	i51	33822	3167.15	0
i12	43284	85.53	0	i32	56976	893.03	0	i52	54704	2608.58	0
i13	62594	106.84	0	i33	52725	327.29	0	i53	40952	3363.26	0
i14	32297	45.47	0	i34	60288	610.95	0	i54	40392	1410.63	0
i15	34674	63.18	0	i35	0	3600.00	100	i55	55917	3600	0
i16	22541	46.78	0	i36	32333	528.04	0	i56	24409	1884.07	0
i17	23872	39.74	0	i37	23628	286.64	0	i57	32097	859.42	0
i18	27871	31.37	0	i38	25673	532.05	0	i58	0	3600.00	100
i19	27768	78.02	0	i39	21396	153.96	0	i59	32790	995.08	0
i20	32762	99.92	0	i40	35356	263.48	0	i60	17110	1144.87	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

We can again observe that with this 2nd method, for the majority of the instances, feasible solutions were produced. Table 9 summarizes the main information about these results.

Table 9 – Main results obtained by the 2nd method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	none	i23, i26, i29, i30 and i35	i44, i50, and i58
instances with GAP different from zero	none	i23, i26, i29, i30 and i35	i44, i50, and i58
maximum execution time	106.84 seconds (i13)	893.06 seconds (i32)	3600.39 seconds (i55)
minimum execution time	27.18 seconds (i18)	153.96 seconds (i39)	859.42 seconds (i57)

3RD METHOD RESULTS

The results of the 3rd method are presented on Table 10.

Table 10 – Results obtained with the 3rd method and objective function cost

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	62909	28.63	0	i21	79087.9	63.13	0	i41	113578	121.56	0
i2	104692	14.09	0	i22	76506.4	31.78	0	i42	188163	105.67	0
i3	98640.5	10.04	0	i23	174142	30.25	0	i43	112395	188.62	0
i4	99656.8	16.31	0	i24	75190.1	80.33	0	i44	103753	131.47	0
i5	98536.9	12.60	0	i25	75799	36.28	0	i45	0	113.52	100
i6	56278.8	8.54	0	i26	52530.8	127.11	0	i46	0	199.77	100
i7	60721.1	13.48	0	i27	59636	76.77	0	i47	76068.5	218.34	0
i8	66149	13.34	0	i28	46136	71.98	0	i48	86256	281.50	0
i9	71853.9	16.15	0	i29	75354.6	151.22	0	i49	70103.1	384.86	0
i10	50599.5	13.00	0	i30	66684	65.29	0	i50	96353.4	321.07	0
i11	31248.3	29.19	0	i31	38949	82.98	0	i51	27027.1	217.70	0
i12	30138.2	17.05	0	i32	44609.6	95.18	0	i52	52562	263.60	0
i13	57266.5	27.04	0	i33	39191	49.50	0	i53	0	3600.00	100
i14	23850.1	8.71	0	i34	0	71.69	100	i54	32094.2	130.19	0
i15	33052.7	11.64	0	i35	49770	38.42	0	i55	0	3600.00	100
i16	19969.8	9.04	0	i36	29526	59.24	0	i56	22635	187.86	0
i17	19969	11.78	0	i37	21690	37.23	0	i57	0	3600	100
i18	20862	9.56	0	i38	24173.5	53.12	0	i58	18838.6	152.81	0
i19	26974	18.09	0	i39	19925	13.06	0	i59	26604	134.80	0
i20	21207	10.10	0	i40	30715.8	14.19	0	i60	16244	118.61	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

With the 3rd method, infeasible solutions were obtained for just five instances from the sixty, all of them being from the Large Instances category. See Table 11 below for a summary of the results with this approach.

Table 11 – Main results obtained by the 3rd method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	none	none	i45, i46, i53, i55 and i57
instances with GAP different from zero	none	none	i45, i46, i53, i55 and i57
maximum execution time	29.19 seconds (i11)	127.11 seconds (i26)	384.86 seconds (i49)
minimum execution time	8.71 seconds (i14)	13.06 seconds (i39)	105.67 seconds (i42)

4TH METHOD RESULTS

Table 12 summarizes the results of the 4th method.

Table 12 – Results obtained with the 4th method and objective function cost

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	62909	28.88	0	i21	89072	95.11	0	i41	127431	928.90	0
i2	104692	15.80	0	i22	92650.4	50.29	0	i42	211817	769.09	0
i3	98640.5	13.94	0	i23	0	3600.00	100	i43	127416	1227.74	0
i4	99656.8	26.94	0	i24	91268.8	481.73	0	i44	0	3600.00	100
i5	98536.9	14.11	0	i25	87095.7	82.77	0	i45	175138	968.31	0
i6	56278.8	9.44	0	i26	84514.8	781.54	0	i46	84627	1481.41	0
i7	60721.1	18.60	0	i27	70181	409.55	0	i47	85359	1652.80	0
i8	66149	14.73	0	i28	60822.4	545.25	0	i48	98694	2092.71	0
i9	71853.9	20.89	0	i29	82630.7	915.84	0	i49	75716	2882.12	0
i10	50599.5	13.50	0	i30	76134.4	81.27	0	i50	100385	3277.46	0
i11	31248.3	24.89	0	i31	43496.6	493.95	0	i51	33822	1662.00	0
i12	30138.2	18.48	0	i32	56975.7	684.64	0	i52	54704	1924.43	0
i13	57266.5	21.56	0	i33	52723.4	87.01	0	i53	40952	2810.95	0
i14	23850.1	13.12	0	i34	60292.1	493.19	0	i54	40392	1080.86	0
i15	33052.7	14.06	0	i35	56448.8	77.90	0	i55	55917	3600.00	0
i16	19969.8	15.62	0	i36	32332.7	371.69	0	i56	24409	1508.55	0
i17	19969	11.75	0	i37	23628.4	44.75	0	i57	32097	659.40	0
i18	20862	8.88	0	i38	25673.1	371.94	0	i58	20380	1138.66	0
i19	26974	15.23	0	i39	21396.2	62.63	0	i59	32788	825.55	0
i20	21207	27.09	0	i40	35371.6	49.71	0	i60	17110	973.60	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

Finally, we can observe that with the 4th method, only for two instances, infeasible solutions were obtained. See Table 13, for a summary of the results.

Table 13 – Main results obtained by the 4th method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	none	i23	i44
instances with GAP different from zero	none	i23	i44
maximum execution time	28.88 seconds (i1)	781.54 seconds (i26)	3600.00 seconds (i50)
minimum execution time	8.88 seconds (i18)	30.48 seconds (i23)	659.40 seconds (i57)

SMALL INSTANCES CHARTS

The charts on Figures 15 and 16 show the objective value and execution time obtained with the different approaches, for the small instances category.

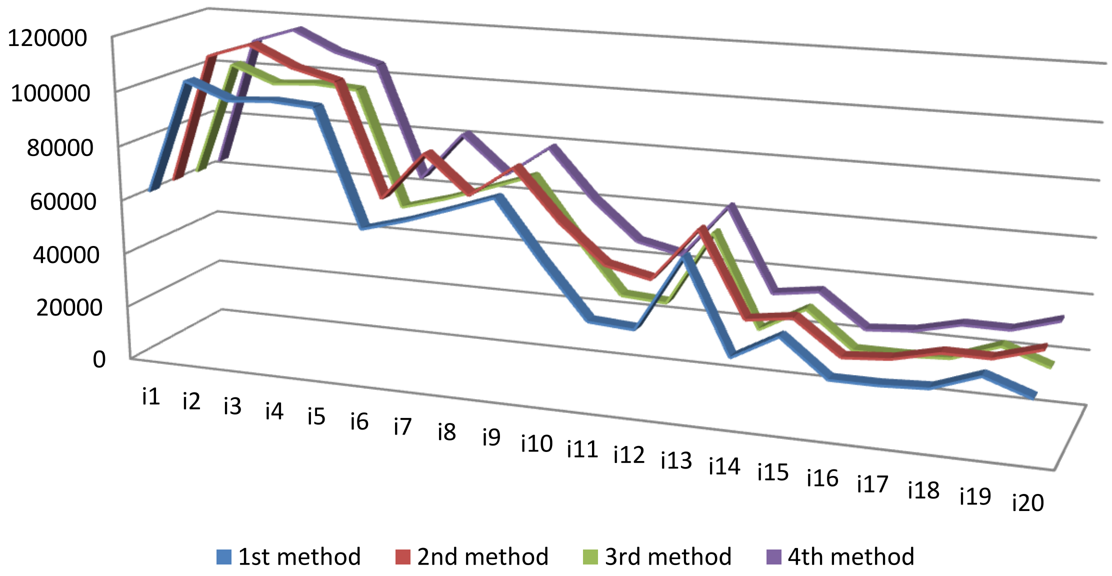


Figure 15 – Objective function cost for the small instances

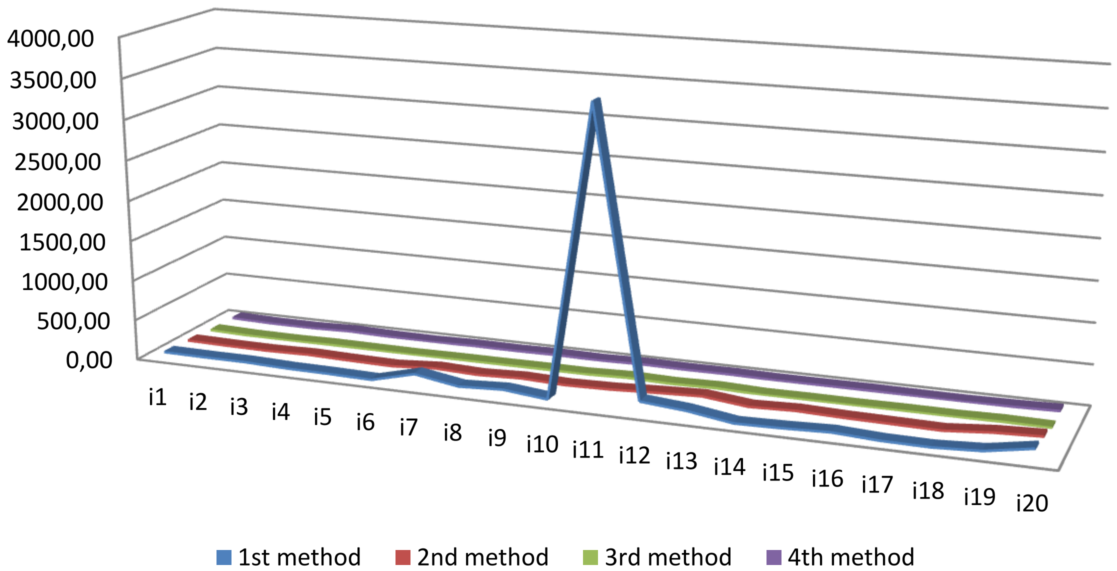


Figure 16 – Execution time for objective function cost, for the small instances

In Figure 17, we present the same chart of the Figure 16, excluding the outlier value from instance “i11”.

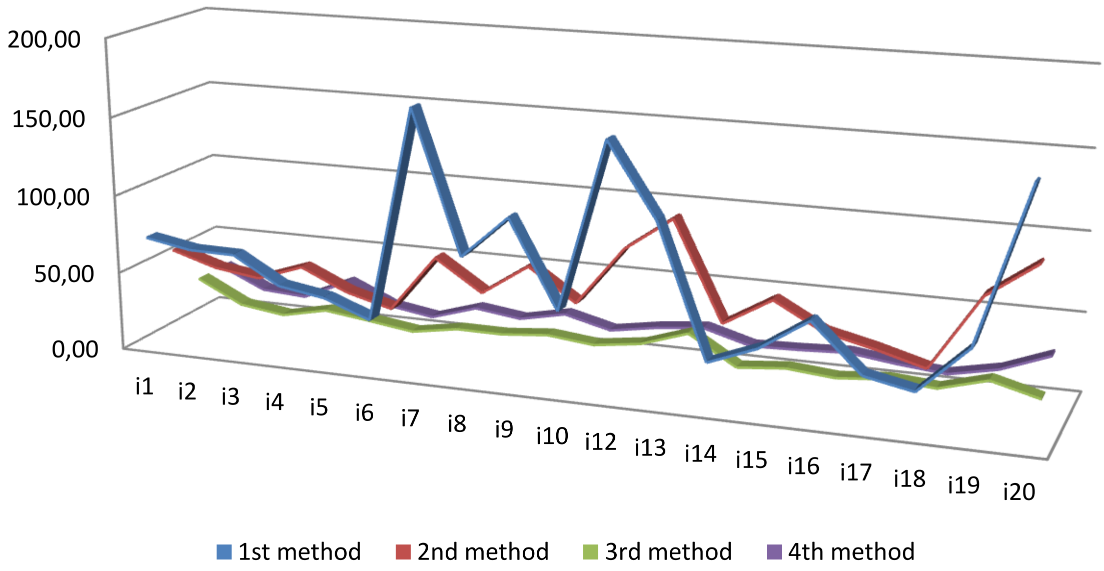


Figure 17 – Execution time for objective function cost, for the small instances, without the outlier “i11”.

MEDIUM INSTANCES CHARTS

The charts for the medium and large instances were developed considering just the instances that presented (feasible) solutions for all the methods.

The two next charts on Figures 18 and 19 present the objective function values and execution time for the four methods in parallel, in instances from the medium category.

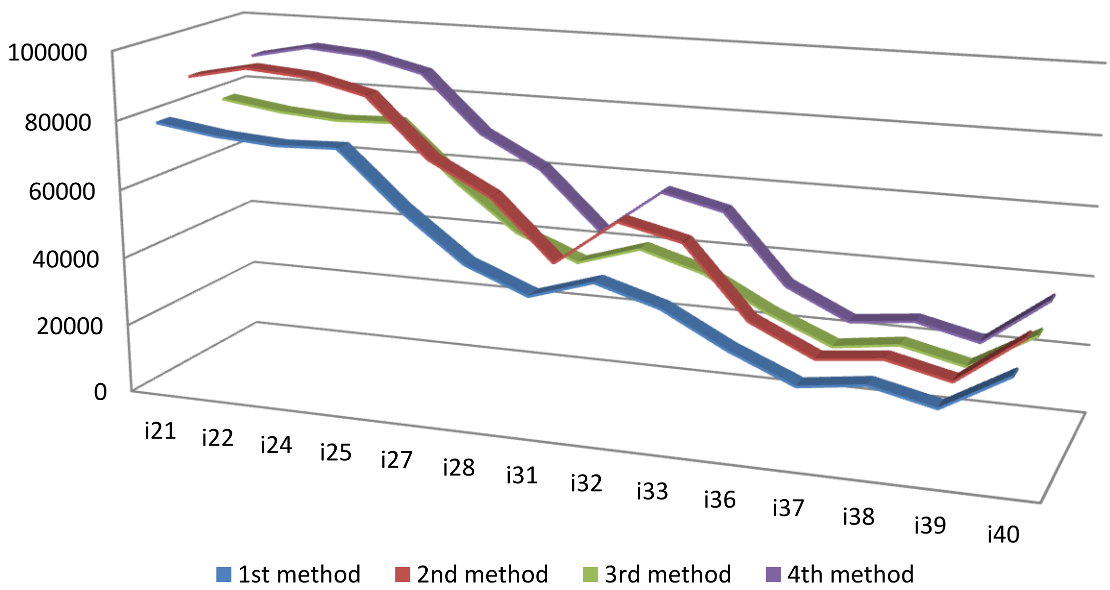


Figure 18 – Objective function cost for the medium instances

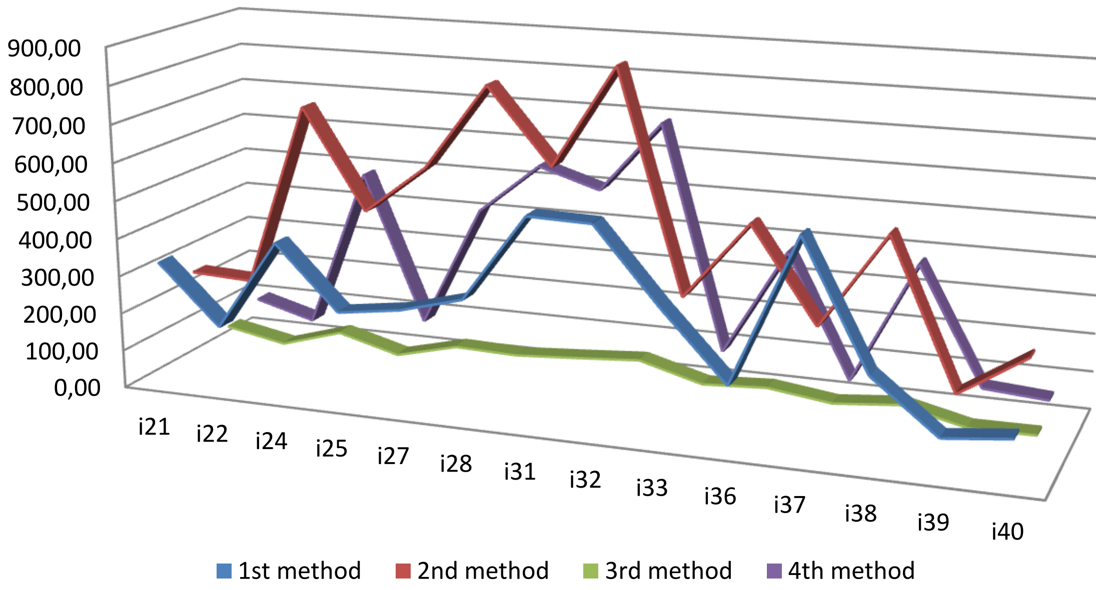


Figure 19 – Execution time for objective function cost, for the medium instances

LARGE INSTANCES CHARTS

Finally, Figures 20 and 21 show, in parallel, the objective function values and execution time for the four methods, in the large instances category.

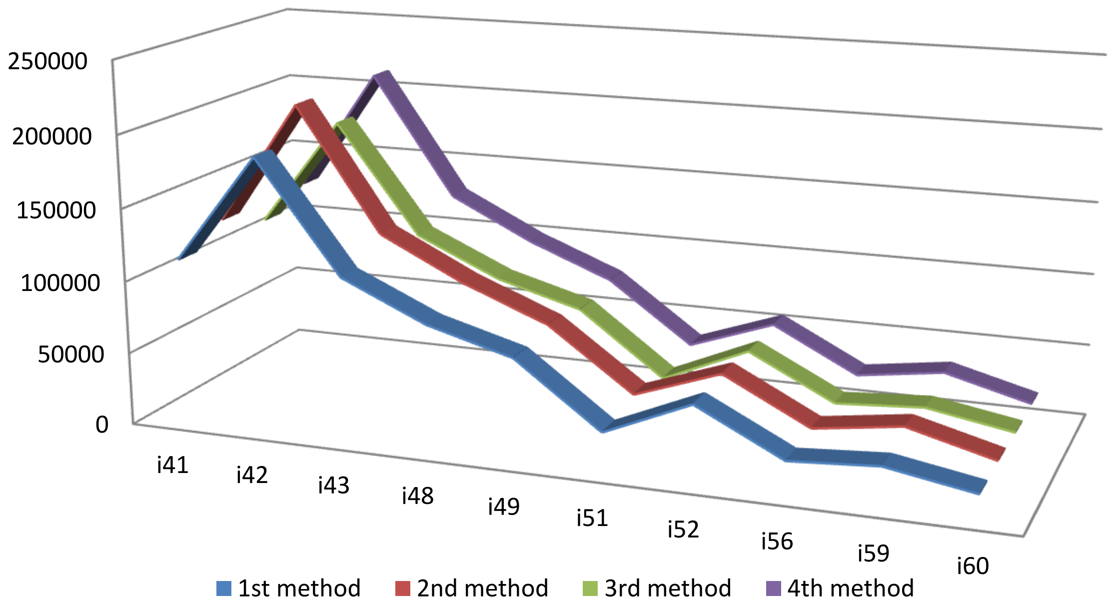


Figure 20 – Objective function cost for the large instances

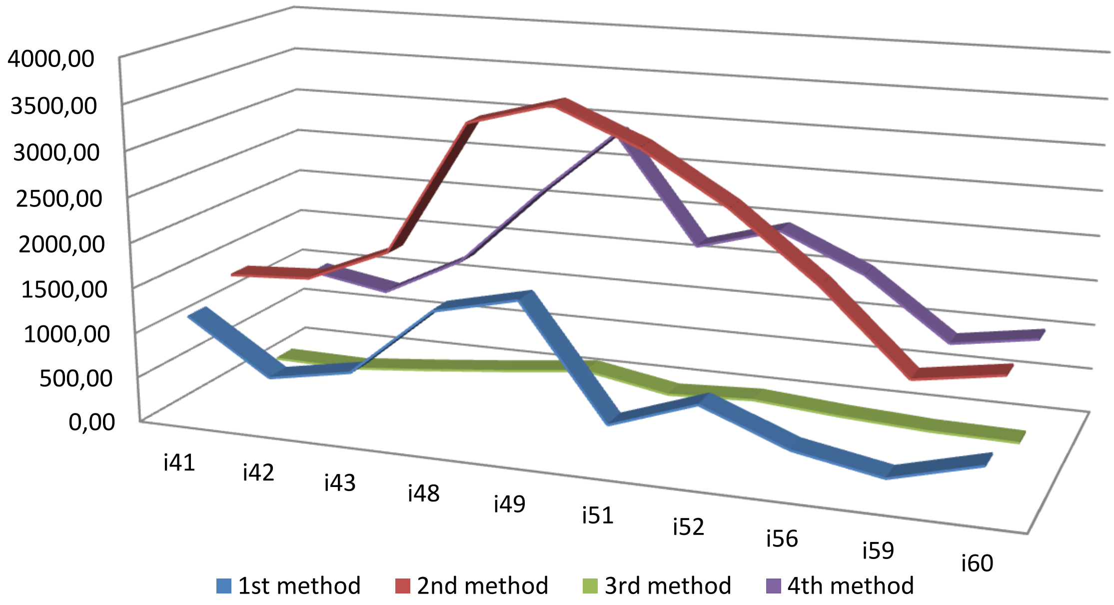


Figure 21 – Execution time for objective function cost, for the large instances

AVERAGE AND STANDARD DEVIATION

Tables 14 and 15 present the average and standard deviation values obtained for the solutions of the three instances categories.

Table 14 – Average values and standard deviation of the cost objective function values

Objective Value					
Statistical measure	Instance type	1st method	2nd method	3rd method	4th method
Average	Small	52728.97	60449.91	52728.755	60450.41
	Medium	52454.7125	55905.31429	47223.95	55906.28571
	Large	73656.70	81820.79	56492.75	83388.57
Standard Deviation	Small	29799.19	31038.18	29798.84	31038.28
	Medium	24960.75	26590.14	21980.35	26589.22942
	Large	54329.96	64369.08	55629.69	62427.47

Table 15 – Average values and standard deviation of the execution time values for the cost objective function

Execution Time					
Statistical measure	Instance type	1st method	2nd method	3rd method	4th method
Average	Small	251.31	58.23	14.92	17.38
	Medium	312.24	482.99	54.62	273.64
	Large	879.73	2229.48	719.81	1414.08
Standard Deviation	Small	790.57	20.98	6.41	5.88
	Medium	154.28	233.09	25.64	227.4202039
	Large	467.13	929.74	1280.65	609.11

ANALISYS OF VARIANCE

Tables 16, 17, 18, and 19 present the results of an analysis of variance for the small instances, with confidence level of 5%. Tables 16 and 17 are for objective function values, while tables 18 and 19 are for the execution time.

Table 16 – Anova single factor summary – Small instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	20	1054579	52728.97	8.88E+08
2nd method	20	1208998	60449.91	9.63E+08
3rd method	20	1054575	52728.76	8.88E+08
4th method	20	1209008	60450.41	9.63E+08

Table 17 – Anova single factor – Small instances – Objective function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1192368705	3	3.97E+08	0.429368	0.732542	2.724944
Inside of the groups	70351417888	76	9.26E+08			
Total	71543786592	79				

Table 18 – Anova single factor summary – Small instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	20	5026.233	251.3117	624999.2
2nd method	20	1164.618	58.2309	440.2826
3rd method	20	298.381	14.91905	41.1138
4th method	20	347.506	17.3753	34.61995

Table 19 – Anova single factor – Small instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	757194.9139	3	252398.3	1.614019	0.193109	2.724944
Inside of the groups	11884789.3	76	156378.8			
Total	12641984.21	79				

Tables 20, 21, 22 and 23 present the analysis of variance results for the medium instances with confidence level of 5%. Tables 20 and 21 are for objective function values, while Tables 22 and 23 are for the execution time.

Table 20 – Anova single factor summary – Medium instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	14	661131.4	47223.67	4.83E+08
2nd method	14	782674.4	55905.31	7.07E+08
3rd method	14	661135.3	47223.95	4.83E+08
4th method	14	782688	55906.29	7.07E+08

Table 21 – Anova single factor – Medium instances – Objective function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1055277139	3	3.52E+08	0.591117	0.623596	2.7826
Inside of the groups	30943901622	52	5.95E+08			
Total	31999178761	55				

Table 22– Anova single factor summary – Medium instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	14	4371.343	312.2388	23802.32
2nd method	14	6761.864	482.9903	54328.93
3rd method	14	764.749	54.62493	657.425
4th method	14	3831.015	273.6439	51719.95

Table 23 – Anova single factor – Medium instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1303059.226	3	434353.1	13.31262	1.45E-06	2.7826
Inside of the groups	1696612.115	52	32627.16			
Total	2999671.341	55				

Tables 24, 25, 26, and 27 present the analysis of variance results for the largeinstances with confidence level of 5%. Tables 24 and 25 are for objective function values, while tables 26 and 27 are for the execution time.

Table 24 – Anova single factor summary – Large instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	10	715567.2	71556.72	3.01E+09
2nd method	10	803902.8	80390.28	3.81E+09
3rd method	10	715567.2	71556.72	3.01E+09
4th method	10	803906.6	80390.66	3.81E+09

Table 25 – Anova single factor – Large instances – Objective function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	780351391.3	3	2.6E+08	0.076313	0.972377	2.866266
Inside of the groups	1.22708E+11	36	3.41E+09			
Total	1.23488E+11	39				

Table 26 – Anova single factor summary – Large instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
1st method	10	8186.745	818.6745	231638.3
2nd method	10	21258.51	2125.851	908637
3rd method	10	2004.77	200.477	7930.624

4th method	10	14794.68	1479.468	458922.3

Table 27 – Anova single factor – Large instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	20720547.63	3	6906849	17.19054	4.29E-07	2.866266
Inside of the groups	14464153.54	36	401782			
Total	35184701.16	39				

It is important to highlight that the 2nd, 3rd and 4th methods generated some extra values important to take into consideration in sense to analyze the results of the methods.

HEURISTICS EXECUTION TIMES

Table 28 presents the values related to the total time reduction from the second method, the relax objective solution and total time relax solution from the Third method.

Table 28 – Total reduction time from the 2nd method, relax objective solution and total time relax solution from the 3rd method

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	7	62909.00	14.1	i21	53	79081.30	38.301	i41	857	113577	89.444
i2	5	104692.00	8.312	i22	22	76506.40	22.259	i42	703	188163	75.479
i3	4	98638.70	5.179	i23	22	174142.00	20.352	i43	1112	112395	111.87
i4	7	99656.80	9.836	i24	428	75190.10	63.26	i44	833	103749	89.389
i5	4	98536.90	5.834	i25	156	75799.00	25.281	i45	875	146410	81.963
i6	2	56278.80	4.054	i26	0	52530.80	89.35	i46	1391	76697	116.41
i7	6	60721.10	7.951	i27	372	59615.40	47.099	i47	1531	76069	134.06
i8	4	66140.60	6.304	i28	497	46135.90	54.992	i48	1938	86256	157.51
i9	8	71853.90	10.1	i29	0	75354.60	107.62	i49	2675	70102	182.68
i10	4	50599.50	6.897	i30	0	66684.00	36.631	i50	0	96353.4	194.41
i11	11	31229	16.06	i31	444	38945.00	59.168	i51	1516	27027	134.31
i12	6	30137.40	10.75	i32	625	44609.60	71.88	i52	1785	52562	139.79
i13	7	57266.50	10.45	i33	52	39191.00	36.684	i53	2548	0	0
i14	2	23850.10	3.734	i34	435	57350.30	48.927	i54	997	32094	84.941
i15	6	33052.70	6.039	i35	0	49770.00	27.931	i55	2748	0	0
i16	3	19969.80	4.02	i36	319	29526.00	43.918	i56	1513	22635	81.457
i17	3	19969.00	5.914	i37	181	21690.00	26.748	i57	646	28821	48.148
i18	4	20862.00	4.904	i38	364	24173.50	34.861	i58	0	18839	94.307
i19	7	26974.00	11.64	i39	66	19925.00	3.083	i59	802	26604	83.959
i20	15	21207.00	2.382	i40	151	30715.80	3.369	i60	887	16244	64.839

I – Instances; II – Total reduction time (2nd method); III – Relax Obj Solution (3rd method); IV – Total time relax solution (3rd method).

The Table 29 presents the same values related to the previous table, but this time overall values are related to the 4th method.

Table 29 – Total reduction time, relax objective solution and total time relax solution from the 4th method.

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	7	62909.00	14.1	i21	53	79081.30	38.301	i41	857	113577	89.444
i2	5	104692.00	8.312	i22	22	76506.40	22.259	i42	703	188163	75.479
i3	4	98638.70	5.179	i23	22	174142.00	20.352	i43	1112	112395	111.87
i4	7	99656.80	9.836	i24	428	75190.10	63.26	i44	833	103749	89.389
i5	4	98536.90	5.834	i25	156	75799.00	25.281	i45	875	146410	81.963
i6	2	56278.80	4.054	i26	0	52530.80	89.35	i46	1391	76697	116.41
i7	6	60721.10	7.951	i27	372	59615.40	47.099	i47	1531	76069	134.06
i8	4	66140.60	6.304	i28	497	46135.90	54.992	i48	1938	86256	157.51
i9	8	71853.90	10.1	i29	0	75354.60	107.62	i49	2675	70102	182.68
i10	4	50599.50	6.897	i30	0	66684.00	36.631	i50	0	96353.4	194.41
i11	11	31229	16.06	i31	444	38945.00	59.168	i51	1516	27027	134.31
i12	6	30137.40	10.75	i32	625	44609.60	71.88	i52	1785	52562	139.79
i13	7	57266.50	10.45	i33	52	39191.00	36.684	i53	2548	0	0
i14	2	23850.10	3.734	i34	435	57350.30	48.927	i54	997	32094	84.941
i15	6	33052.70	6.039	i35	0	49770.00	27.931	i55	4342	0	0
i16	3	19969.80	4.02	i36	319	29526.00	43.918	i56	1513	22635	81.457
i17	3	19969.00	5.914	i37	181	21690.00	26.748	i57	646	28821	48.148
i18	4	20862.00	4.904	i38	364	24173.50	34.861	i58	0	18839	94.307
i19	7	26974.00	11.64	i39	66	19925.00	3.083	i59	802	26604	83.959
i20	15	21207.00	2.382	i40	151	30715.80	3.369	i60	887	16244	64.839

I – Instances; II – Total reduction time (4th method); III – Relax Obj Solution (4th method); IV – Total time relax solution (4th method).

6.2.2. Objective function *time*

Results are presented in the tables below. Note that for infeasible instances, the values of the objective functions were plotted as zero. For the 1st method, see Table 30.

1ST METHOD RESULTS

The results of the 1st method are presented on Table 30.

Table 30 – Results obtained with the 1st method and objective function time

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	1645	3600.00	1.85465	i21	0	3600.00	100	i41	0	3600.00	100
i2	0	3600.00	100	i22	0	3600.00	100	i42	0	3600.00	100
i3	2722	3600.00	1.42603	i23	0	3600.00	100	i43	0	3600.00	100
i4	2336	3600.00	1.33263	i24	0	3600.00	100	i44	0	3600.00	100
i5	1539	3600.00	1.58368	i25	0	3600.00	100	i45	0	3600.00	100
i6	1052	3600.00	2.12454	i26	0	3600.00	100	i46	0	3600.00	100
i7	1314	3600.00	2.18211	i27	0	3600.00	100	i47	0	3600.00	100
i8	1922	3600.00	1.22785	i28	0	3600.00	100	i48	64949	3600.00	99.7009
i9	1141	3600.00	3.02687	i29	0	3600.00	100	i49	0	3600.00	100
i10	1188	3600.00	2.07015	i30	0	3600.00	100	i50	0	3600.00	100
i11	820	3600.00	3.36821	i31	0	3600.00	100	i51	62206	3600.00	99.7627
i12	705	3600.00	3.66936	i32	0	3600.00	100	i52	0	3600.00	100
i13	772	3600.00	3.56287	i33	756	3600.00	9.97694	i53	0	3600.00	100
i14	742	3600.00	3.90624	i34	0	3600.00	100	i54	0	3600.00	100
i15	824	3600.00	2.52854	i35	618	3600.00	7.01208	i55	0	3600.00	100
i16	529	3600.00	3.91499	i36	0	3600.00	100	i56	0	3600.00	100
i17	397	3600.00	4.04611	i37	346	3600.00	7.4952	i57	328	3600.00	20.7443
i18	439	3600.00	3.57043	i38	309	3600.00	8.58282	i58	8805	3600.00	99.0726
i19	0	3600.00	100	i39	338	3600.00	8.00809	i59	0	3600.00	100
i20	348	3600.00	4.86964	i40	400	3600.00	8.43065	i60	141842	3600.00	99.9424

I – Instances; II – Objective Value; III – Time; IV – Gap.

We can observe that with the 1st method, for the majority of the instances, feasible solutions were produced. Table 31 summarizes the main information about these results.

Table 31 – Main results obtained by the 1st method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	i2 and i19	i21 to i32, i34 and i36	i41 to i47, i49, i50, i52 to i56 and i59
instances with GAP different from zero	all	all	all
maximum execution time	3600 seconds (all)	3600 seconds (all)	3600 seconds (all)
minimum execution time	3600 seconds (all)	3600 seconds (all)	3600 seconds (all)

2ND METHOD RESULTS

The results of the 2nd method are presented on Table 32.

Table 32 – Results obtained with the 2nd method and objective function time

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	0	3600.00	100	i21	0	3600.00	100	i41	1876	3600	9.29609
i2	2571	3600.00	1.22463	i22	0	3600.00	100	i42	0	3600	100
i3	3232	3600.00	1.22326	i23	0	3600.00	100	i43	0	3600	100
i4	0	3600.00	100	i24	0	3600.00	100	i44	0	3600	100
i5	1697	3600.00	1.43968	i25	2178	3600.00	1.9017	i45	0	3600	100
i6	1165	3600.00	1.86735	i26	1427	3600.00	9.91946	i46	49308	3600	99.5912
i7	1486	3600.00	1.95929	i27	1334	3600.00	4.51406	i47	0	3600	100
i8	2150	3600.00	1.47301	i28	1112	3600.00	6.30866	i48	63124	3600	99.6772
i9	1336	3600.00	1.91125	i29	1157	3600.00	6.2727	i49	216406	3600	99.9976
i10	1329	3600.00	2.04932	i30	0	3600.00	100	i50	62362	3600	100
i11	1077	3600.00	2.4668	i31	840	3600.00	9.99768	i51	52797	3600	99.7179
i12	829	3600.00	2.90299	i32	844	3600.00	18.9684	i52	15733	3600	99.9701
i13	961	3600.00	2.09984	i33	839	3600.00	4.80473	i53	188713	3600	99.9973
i14	827	3600.00	2.45046	i34	824	3600.00	6.41212	i54	4467	3600	90.7163
i15	860	3600.00	2.94423	i35	0	3600.00	100	i55	0	3600	100
i16	622	3600.00	2.71352	i36	510	3600.00	6.15079	i56	25329	3600	99.9824
i17	468	3600.00	3.30557	i37	375	3600.00	5.15442	i57	344	3600	10.6165
i18	576	3600.00	1.9838	i38	342	3600.00	6.36926	i58	2845	3600	99.8358
i19	348	3600.00	4.11063	i39	369	3600.00	6.29666	i59	2399	3600	88.0416
i20	0	3600.00	100	i40	437	3600.00	6.56215	i60	103466	3600	99.7649

I – Instances; II – Objective Value; III – Time; IV – Gap.

We can again observe that with this 2nd method, for the majority of the instances, feasible solutions were produced. Table 33 summarizes the main information about these results.

Table 33 – Main results obtained by the 2nd method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	i1 and i4	i21 to i24, i30, i35	i42 to i45, i47, i55
instances with GAP different from zero	all	all	all
maximum execution time	3600 seconds (all)	3600 seconds (all)	3600 seconds (all)
minimum execution time	3600 seconds (all)	3600 seconds (all)	3600 seconds (all)

3RD METHOD RESULTS

The results of the 3rd method are presented on Table 34.

Table 34 – Results obtained with the 3rd method and objective function time

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	1890	52.90	0	i21	2031	225.58	0	i41	1809	586.443	0
i2	0	3600.00	100	i22	1786	125.65	0	i42	0	3600	100
i3	3182	65.16	0	i23	2063	115.03	0	i43	2142	562.708	0
i4	2907	41.93	0	i24	0	3600.00	100	i44	0	3600	100
i5	1923	59.91	0	i25	2145	148.27	0	i45	0	3600	100
i6	1292	20.93	0	i26	1324	424.44	0	i46	1128	682.525	0
i7	1504	35.79	0	i27	1432	194.66	0	i47	0	3600	100
i8	2137	43.97	0	i28	1082	270.30	0	i48	1052	709.438	0
i9	1511	63.68	0	i29	1248	466.00	0	i49	0	3600	100
i10	1520	105.05	0	i30	1146	228.75	0	i50	0	795.127	0
i11	962	62	0	i31	878	238.14	0	i51	687	878.413	0
i12	855	42.27	0	i32	798	327.32	0	i52	713	968.356	0
i13	884	46.45	0	i33	885	192.63	0	i53	0	3600	100
i14	943	28.78	0	i34	817	222.52	0	i54	0	3600	100
i15	966	31.82	0	i35	756	192.30	0	i55	0	3600	100
i16	602	38.54	0	i36	512	246.73	0	i56	361	562.167	0
i17	465	46.20	0	i37	395	119.41	0	i57	365	397.966	0
i18	503	57.26	0	i38	385	212.53	0	i58	377	437.454	0
i19	400	41.72	0	i39	392	108.13	0	i59	397	414.688	0
i20	423	57.41	0	i40	447	139.63	0	i60	363	423.397	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

With the 3rd method, infeasible solutions were obtained for nine instances from the sixty. See Table 35 below for a summary of the results with this approach.

Table 35 – Main results obtained by the 3rd method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	i2	i24	i42, i44, i45, i47, i49, i53 to i55
instances with GAP different from zero	i2	i24	i42, i44, i45, i47, i49, i53 to i55
maximum execution time	105.05 seconds (i10)	424.44 seconds (i26)	968.35 seconds (i52)
minimum execution time	20.93 seconds (i6)	108.13 seconds (i39)	397.96 seconds (i57)

4TH METHOD RESULTS

Table 36 summarizes the results of the 4th method.

Table 36 – Results obtained with the 4th method and objective function time

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	2006	56.53	0	i21	2196	191.62	0	i41	2060	1209.44	0
i2	2793	31.83	0	i22	2267	84.42	0	i42	3027	1109.82	0
i3	3611	75.23	0	i23	0	3600	100	i43	2425	1499.24	0
i4	3146	190.28	0	i24	2216	589.75	0	i44	0	3600.0	100
i5	2034	103.58	0	i25	2377	146.73	0	i45	0	3600.0	100
i6	1412	19.06	0	i26	1598	967.62	0	i46	1251	1761.17	0
i7	1657	33.38	0	i27	1566	512.90	0	i47	1186	2227.05	0
i8	2391	44.42	0	i28	1240	697.81	0	i48	1218	2453.36	0
i9	1718	42.03	0	i29	1314	1179.24	0	i49	1366	3443.3	0
i10	1628	77.02	0	i30	1317	172.14	0	i50	1405	3600.0	0
i11	1218	51	0	i31	924	592.11	0	i51	749	1940.46	0
i12	997	35.31	0	i32	876	828.95	0	i52	761	2544.11	0
i13	1090	38.22	0	i33	1020	165.02	0	i53	986	3272.97	0
i14	1024	19.26	0	i34	934	571.19	0	i54	760	1323.91	0
i15	1003	30.76	0	i35	913	306.54	0	i55	0	3600.0	100
i16	678	22.85	0	i36	579	460.19	0	i56	388	1895.7	0
i17	526	26.01	0	i37	431	110.38	0	i57	397	891.366	0
i18	646	64.90	0	i38	427	498.51	0	i58	406	1288.84	0
i19	464	40.97	0	i39	417	105.97	0	i59	451	1144.67	0
i20	537	65.33	0	i40	498	123.57	0	i60	369	1316.18	0

I – Instances; II – Objective Value; III – Time; IV – Gap.

Finally, we can observe that with the 4th method, only for four instances, infeasible solutions were obtained. See Table 37, for a summary of the results.

Table 37 – Main results obtained by the 4th method

Feature	Small Instances	Medium Instances	Large Instances
infeasible instances	none	i23	i44, i45,and i55
instances with GAP different from zero	none	i23	i44, i45,and i55
maximum execution time	290.28 seconds (i4)	1179.24 seconds (i29)	3600.00 seconds (i50)
minimum execution time	19.06seconds (i6)	84.42 seconds (i22)	891.36 seconds (i57)

The charts for the small, medium and large instances were developed considering just the instances that presented (feasible) solutions for all the methods.

SMALL INSTANCES CHARTS

The charts on figures 22 and 23 show the objective values and execution time obtained with the different approaches, for the small instances category.

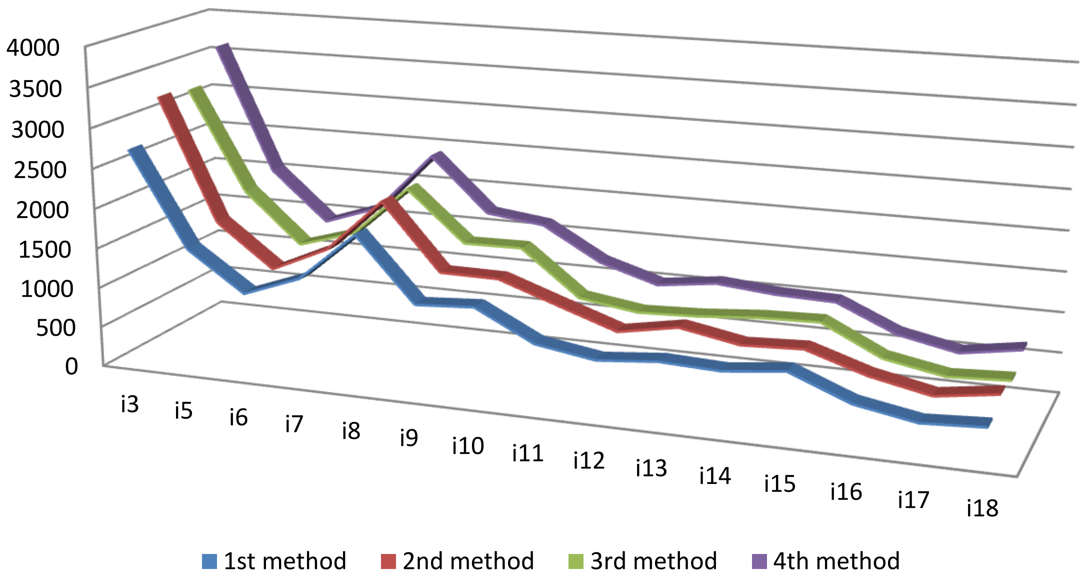


Figure 22 – Objective function cost prospection for the small instances

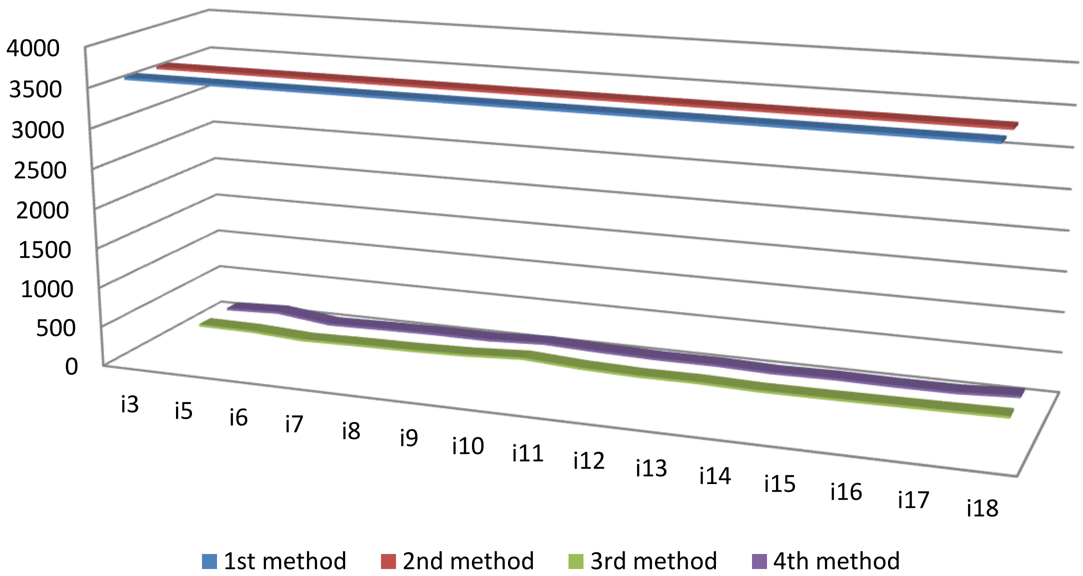


Figure 23 – Execution time for objective function cost prospection for the small instances

MEDIUM INSTANCES CHARTS

The two next charts on Figures 24 and 25 present the objective function values and execution times for the four methods in parallel, in instances from the medium category.

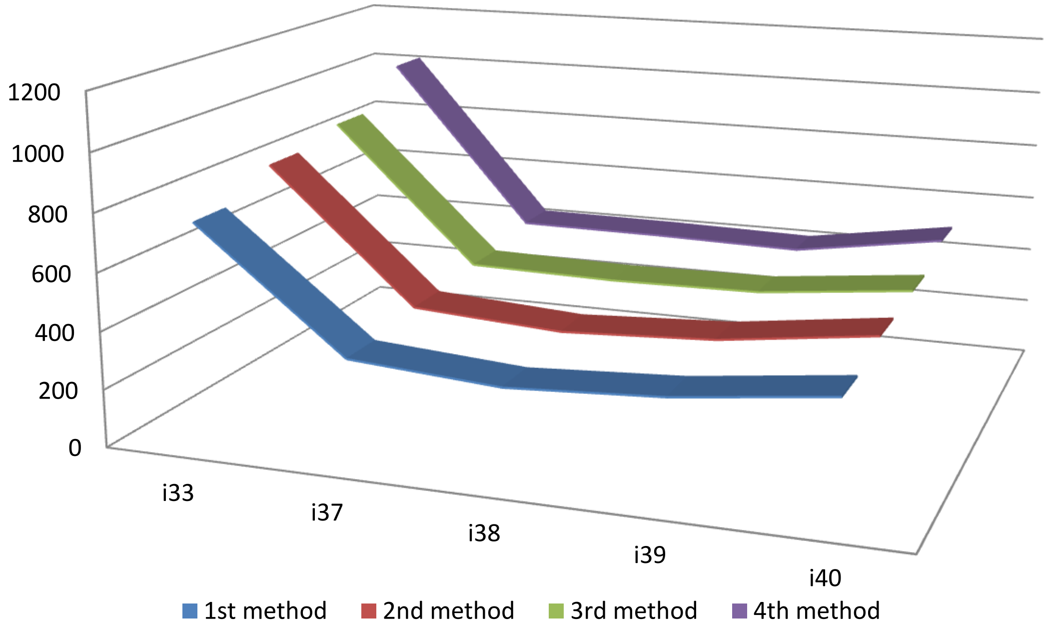


Figure 24 – Objective function cost prospection for the medium instances

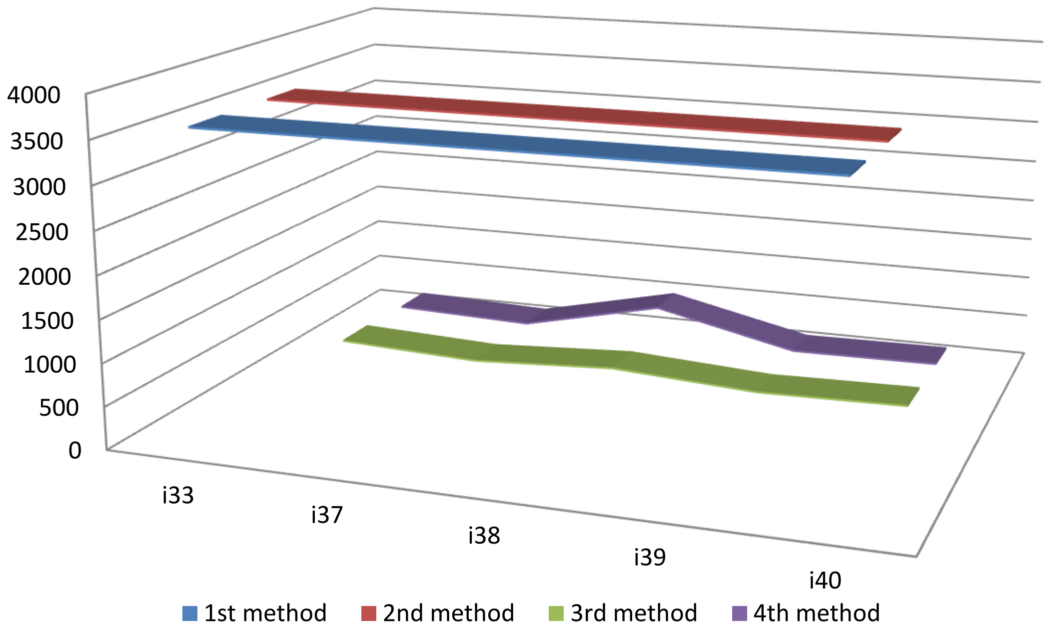


Figure 25 – Execution time for objective function cost prospection for the medium instances

LARGE INSTANCES CHARTS

Finally, Figures 26 and 27 show, in parallel, the objective function values and execution times for the four methods, in the large instances category.

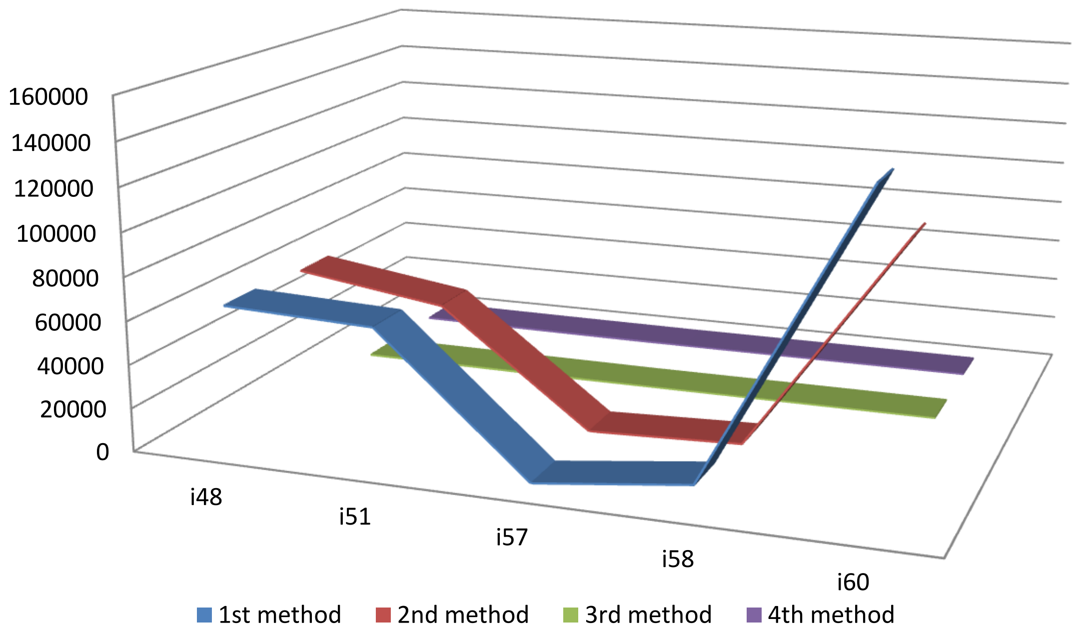


Figure 26 – Objective function cost prospection for the large instances

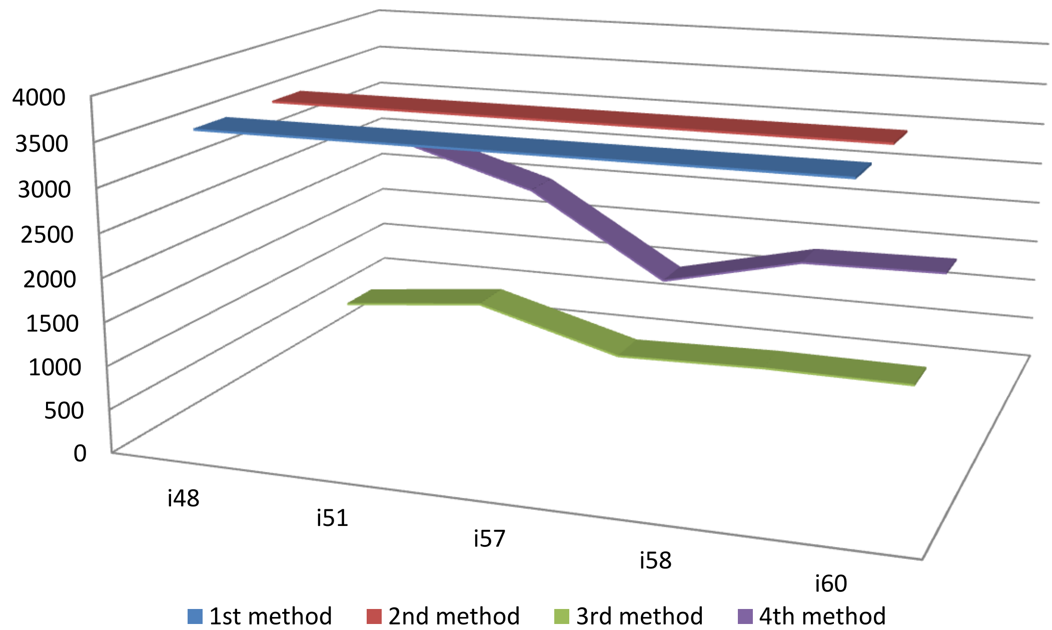


Figure 27 – Execution time for objective function cost prospection for the large instances

AVERAGE AND STANDARD DEVIATION

Tables 38 and 39 present the average and standard deviation values obtained for the solutions of the three instances categories.

Table 38 – Average values and standard deviation of the time objective function values

Objective Value					
Statistical measure	Instance type	1st method	2nd method	3rd method	4th method
Average	Small	1073.7	1241	1283.2	1442.2
	Medium	429.8	472.4	500.8	558.6
	Large	55626	44515.2	568.8	627.8
Standard Deviation	Small	618.18	711.91	722.35	797.74
	Medium	185.29	207.86	216.19	259.91
	Large	56598.34	43524.63	303.37	364.85

Table 39 – Average values and standard deviation of the execution time values related to the time objective function

Execution Time					
Statistical measure	Instance type	1st method	2nd method	3rd method	4th method
Average	Small	3600.00	3600.00	49.82	45.50
	Medium	3600.00	3600.00	154.47	200.69
	Large	3600.00	3600.00	569.33	1578.04
Standard Deviation	Small	0.00	0.00	20.38	24.59
	Medium	0.00	0.00	45.89	168.11
	Large	0.00	0.00	214.02	616.70

ANALISYS OF VARIANCE

Tables 40, 41, 42, and 43 present the results of an analysis of variance for the small instances, with confidence level of 5%. Tables 40 and 41 are for objective function values, while tables 42 and 43 are for the execution time.

Table 40 – Anova single factor summary – Small instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
First method	15	16106	1073.733	382141.8
Second method	15	18615	1241	506812.9
Third method	15	19249	1283.267	521785.1
Fourth method	15	21633	1442.2	636388.6

Table 41 – Anova single factor – Small instances – Objective function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1031917	3	343972,2	0,672107	0,572744	2,769431
Inside of the groups	28659796	56	511782,1			
Total	29691713	59				

Table 42 – Anova single factor summary – Small instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
First method	15	16106	1073.733	382141.8
Second method	15	18615	1241	506812.9
Third method	15	19249	1283.267	521785.1
Fourth method	15	21633	1442.2	636388.6

Table 43 – Anova single factor – Small instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1031917	3	343972.2	0.672107	0.572744	2.769431
Inside of the groups	28659796	56	511782.1			
Total	29691713	59				

Tables 44, 45, 46, and 47 present the analysis of variance results for the medium instances with confidence level of 5%. Tables 44 and 45 are for objective function values, while tables 46 and 47 are for the execution time.

Table 44 – Anova single factor summary – Medium instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
First method	5	2149	429.8	34334.2
Second method	5	2362	472.4	43207.8
Third method	5	2504	500.8	46736.2
Fourth method	5	2793	558.6	67553.3

Table 45 – Anova single factor – Medium instances – Objective Function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	43778.8	3	14592.93	0.304286	0.821883	3.238872
Inside of the groups	767326	16	47957.88			
Total	811104.8	19				

Table 46 – Anova single factor summary – Medium instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
First method	5	18000	3600	0
Second method	5	18000	3600	0
Third method	5	772.328	154.4656	2105.987
Fourth method	5	1003.438	200.6876	28261.24

Table 47 – Anova single factor – Medium instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	58570251	3	19523417	2571.643	1.12E-21	3.238872
Inside of the groups	121468.9	16	7591.806			
Total	58691720	19				

Tables 48, 49, 50, and 51 present the analysis of variance results for the large instances with confidence level of 5%. Tables 48 and 49 are for objective function values, while tables 50 and 51 are for the execution time.

Table 48 – Anova single factor summary – Large instances – Objective function

Group	*Count*	*Sum*	*Average*	*Variance*
First method	5	278130	55626	3.2E+09
Second method	5	222576	44515.2	1.89E+09
Third method	5	2844	568.8	92032.2
Fourth method	5	3139	627.8	133116.7

Table 49 – Anova single factor – Large instances – Objective function

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	1.25E+10	3	4.18E+09	3.281339	0.04821	3.238872
Inside of the groups	2.04E+10	16	1.27E+09			
Total	3.29E+10	19				

Table 50 – Anova single factor summary – Large instances – Execution time

Group	*Count*	*Sum*	*Average*	*Variance*
First method	5	18000	3600	0
Second method	5	18000	3600	0
Third method	5	2846.668	569.3336	45803.97
Fourth method	5	7890.206	1578.041	380315.5

Table 51 – Anova single factor – Large instances – Execution time

Variation source	*SQ*	*gl*	*MQ*	*F*	*P-value*	*Critic F*
Between groups	34455004	3	11485001	107.8102	7.97E-11	3.238872
Inside of the groups	1704478	16	106529.9			
Total	36159482	19				

As in the cost objective function, it is important to highlight that the 2nd, 3rd, and 4th methods generated some extra values important to take into consideration in sense to analyze the results of the methods.

Table 52 presents the values related to the total time reduction the 2nd method, the relax objective solution and total time relax solution from the 3rd method.

Table 52 – Total reduction time for the 2nd method, relax objective solution and total time relax solution for the 3rd method

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	0	4.87	35.75	i21	56	6.40	141.05	i41	831	4.8799	315.8
i2	5	0.00	0	i22	0	5.36	82.878	i42	688	0	0
i3	5	6.96	17.31	i23	22	6.79	73.618	i43	1076	5.0749	396.21
i4	7	7.31	25.56	i24	0	0.00	0	i44	810	0	0
i5	4	5.38	22.07	i25	30	6.09	101.68	i45	859	0	0
i6	3	5.86	12.32	i26	687	5.65	346.84	i46	1355	4.5369	368.09
i7	8	6.39	24.78	i27	354	5.38	153.01	i47	1486	0	0
i8	4	8.47	20.04	i28	479	4.76	211.17	i48	1896	4.5929	520.86
i9	8	5.72	31.03	i29	777	4.90	381.29	i49	2630	0	0
i10	4	6.01	19.13	i30	50	5.03	116.6	i50	2963	4.8	671.79
i11	11	6	31.93	i31	425	4.87	192.82	i51	1473	4.3465	547.48
i12	6	5.43	26.71	i32	603	5.05	283.59	i52	1738	4.4868	536.09
i13	7	5.15	19.61	i33	57	5.28	118.19	i53	2486	0	0
i14	2	5.83	14.91	i34	420	4.90	186.92	i54	967	0	0
i15	5	6.17	19.1	i35	36	4.79	105.02	i55	0	0	0
i16	3	7.03	15.21	i36	309	5.21	150.25	i56	1479	4.2184	387.14
i17	4	4.93	16.92	i37	107	4.56	97.748	i57	640	4.3886	283.99
i18	4	5.66	14.15	i38	359	4.66	175.71	i58	963	4.3412	332.09
i19	8	5.49	32.12	i39	32	4.63	82.405	i59	799	4.8389	286.02
i20	0	5.23	46.26	i40	40	5.29	104.4	i60	880	4.3335	332.91

I – Instances; II – Total reduction time (Second method); III – Relax Obj Solution (Third method); IV – Total time relax solution (Third method).

Table 53 presents the same values related to the previous table, but this time overall values are related to the 4th method.

Table 53 – Total reduction time from the second method, relax objective solution and total time relax solution from the 4th method

Small Instances				Medium Instances				Large Instances			
I	II	III	IV	I	II	III	IV	I	II	III	IV
i1	7	5.22	27.09	i21	52	6.87	88.945	i41	831	5.5753	246.5
i2	5	6.72	16.58	i22	22	6.78	44.083	i42	685	6.8214	237.99
i3	4	7.87	12.23	i23	21	0.00	2.499	i43	1070	5.6531	312.42
i4	8	7.90	22.42	i24	411	6.89	138.81	i44	805	0	8.937
i5	4	5.81	12.6	i25	34	6.84	77.65	i45	866	7.6542	196.47
i6	2	6.73	8.078	i26	688	6.31	243.2	i46	1363	4.9308	242.69
i7	7	7.02	14.98	i27	360	6.02	121.42	i47	1463	4.9054	375.92
i8	4	9.59	13.36	i28	487	5.40	145.31	i48	1876	5.1558	377.72
i9	8	6.68	20.81	i29	786	5.32	283.74	i49	2615	5.2111	504.97
i10	4	6.35	13.68	i30	45	5.42	89.306	i50	2935	5.4	561.06
i11	10	7	23.65	i31	429	5.18	136.17	i51	1456	4.5943	411.2
i12	5	6.12	17.8	i32	607	5.61	178.68	i52	1775	4.7042	422.07
i13	6	6.09	16.66	i33	48	6.33	89.291	i53	2536	5.1844	569.45
i14	2	6.48	10.06	i34	424	5.46	113.67	i54	982	5.0514	270.41
i15	4	6.54	14.7	i35	70	5.44	75.71	i55	0	0	0
i16	3	7.97	9.47	i36	312	5.86	104.66	i56	1499	4.4697	319.11
i17	3	5.41	10.5	i37	40	4.99	54.791	i57	639	4.6896	218.56
i18	3	6.79	9.843	i38	351	5.09	122.43	i58	986	4.6715	265.82
i19	7	5.94	23.61	i39	29	5.04	51.781	i59	820	5.4923	233.69
i20	18	6.56	29.11	i40	35	5.80	67.821	i60	904	4.3554	278.26

I – Instances; II – Total reduction time (Fourth method); III – Relax Obj Solution (Fourth method); IV – Total time relax solution (Fourth method).

6.3. Results Analysis

In this section we will analyze the results presented above, for the tests on the generated problem instances concerning the two different objective functions (cost and time).

6.3.1. Objective function *cost*

6.3.1.1. Infeasible instances

In relation to the objective function *cost* (Tables 7, 9, 11, and 13), the 1st method runs a total of 55 instances, and the 5 infeasible instances are from the large instances set. The 2nd method runs a total of 52 instances, and the infeasible instances are 5 from the medium instances set and 3 from the large instances set (this is the worst result from the four methods). The 3rd method runs a total of 55 instances (like the 1st method), and the 5 infeasible instances are from the large instances set. Finally, the 4th method runs 59 instances, and the only infeasible instance is also from the large instances set (this is the best result from the four methods).

6.3.1.2. Gap values

In relation to the gap values, it should be noted that in general gaps are zero or very close to zero. But in order to provide a comparison between the four methods, this information was taken into consideration, even if it is not so relevant.

The 4th method obtained the best result in this aspect, with 2 instances with gap values different from zero, one from the medium set, and one from the big set. The 2nd method presents the worst result in this aspect, with 8 instances with gap different from zero: 5 from the medium set, and 3 instances from the large instances set. The 3rd method obtained 5 instances with gap different from zero, with 5 from the large instances category. The 1st method produced 5 gap values different from zero, with all 5 being from the large category.

6.3.1.3. Maximum and minimum values

Concerning the maximum and minimum times obtained in the instances, it is possible to observe that the first method obtained 168.99 (worse value for the four methods) and 27.18 (worse value, drawing with the second method) seconds, respectively for the small instances, 833.9 and 100.12 seconds for the medium instances, and 1708.39 and 358.24 seconds for the large instances.

The second method obtained the following results: 106.84 and 27.18 seconds (maximum and minimum values of execution times, respectively) for the small instances; 893.06 and 153.96 seconds for the medium instances (the worst values for the four methods); and finally 3600 (the lime limit, drawing with the fourth method) and 859.42 seconds (the worst value).

The third method obtained the following results: 29.19 and 8.71 seconds (the best value for the four methods) from the small instances category; 127.11 and 13.06 seconds for the medium instances (the best values); and 384.86, and 105.67 (the best values between the four methods) from large instances. Finally, the fourth method obtained the following times: 28.88 and 8.88 seconds (being 28.88 the best value) from small instances; 781.54 and 30.48 seconds from the medium instances; and at least, 3600 (the worse value, drawing with the second method) and 659 seconds, from the large instances category.

6.3.1.4. General terms results

In general terms of the objective function results for the small instances, as presented in Figure 15, we can observe that the 1st and 3rd methods obtained results slightly better than the 2nd and 4th methods. It happens because when the edges structure is reduced by size reduction procedure, the algorithm has fewer arcs to generate a result. The same can be observed in the medium and large instances, looking at the Figures 18 and 20.

The execution time results for small instances, presented in the the Figure 17, allows to observe that the 3rd method obtained the best results, being closing followed by the 4th method. The 2nd method for the first five instances, obtained results a little bit worse than the 3rd and 4th methods. The execution times of the 2nd method worsen a little in relation to the 3rd and 4th methods from the seventh instance and keep itself a higher than the other two until the sixteenth instance, when stayed close again, getting worse one more time at the instances nineteen and twenty. The same effect happens with the 1st method, but with the worse execution times in general terms. We can observe yet, in Figure 16, the presence of an outlier value at the eleventh instance, marking the worse time execution of this instance category. In relation to the medium instances category, we can observe a higher diversified result in Figure 19, with the 3rd method obtaining the best results of execution time, being followed by the 1st method with the 4th method obtaining a little bit worse results and the 2nd method in the last position. The same occurs for the large instances category.

It is important to highlight that the size-reduction procedure, present in the 2nd and 4th methods wasted almost fifty percent of the total algorithm time for large instances in the 2nd method and approximately ninety percent of the time to the same case in the 4th method. So that, we can conclude that the procedure is not so efficient in terms of time when we have a lot of arcs in the edges structure to analyze.

6.3.1.5. Average values and standard deviation

In terms of the average values of the objective function, we can observe in the Table 14 that the 1st and 3rd methods obtained results slightly better than the 2nd and 4th methods for the small instances. To medium instances, the 3rd method presented the best result, being followed by the 1st method and so, the 2nd and 4th methods staying close to each other. The same occurs to the large instances with the difference that the 2nd method average value it was significantly better than the 4th method. However, the standard deviation values it was higher for overall instances, which characterizes a higher level of dispersion between the data values.

In Table 15 we can observe the average values related to the execution times. To small instances, the 3rd method obtained the best value, being followed by the 4th method, 2nd method and the 1st method obtaining the worse result. To medium instances the 3rd method maintains the first position being followed by the 4th method, 1st method and the 2nd method with the last position. To the large instances the comparison performed the following configuration, from the best position to the worst: 3rd method, 1st method 4th method and 2nd method. The standard deviations values in average log it was higher for overall results from the large instances (specially for the third and 2nd method) and medium instances (except for the third method), featuring a high level of data dispersion. To small instances the standard deviation values were low, except for the 1st method, probably because of the outlier value from the eleventh instance.

6.3.1.6. Analysis of variance

About the analysis of variance for objective function values of the small instances, observing the Table 17, we can percept that the *P-value* (0.732542) it was higher than the estimated error (0.05) which means that we must accept the equality between the four samples (one for each method). We can accept this observing too that the value of *F* (0.429368) is less that the value presented in the *Critic F* (2.724944).

We can conclude the same for the execution time in Table 19. The *P-value* (0.193109) is bigger than the estimated error (0.05). Besides that, the value of *F* (1.614019) is inferior of the *Critic F* value (2.724944), so we can to accept the equality between the four samples.

Observing now the analysis of variance related to the medium instances objective function on the Table 21, the *P-value* (0.623596) is bigger than the estimated error (0.05) and the value of *F* (0.591117) is less than the value of *Critic F* (2.7826), which means that we can accept the equality between the four samples. About the medium instances execution time on Table 23, the *P-value* (1.42E-06) is less than the estimated error (0.05), and the value of *F* (13.31262) is bigger than the *Critic F* (2.7826) value so that we can refuse the equality between the four samples.

In analysis of variance to the bigger instances objective function values in the Table 25 it is important to percept that the *P-value* (0.972377) is bigger than the estimated error (0.05), and the value of *F* (0.076313) is less than the value of *Critic F* (2.866266), which means that we can accept the equality between the four samples. About the execution values in Table 27, it is necessary to refuse the equality between the four samples, because the *P-value* (4.29E-07) is less than the estimated error (0.05) and the value of *F* (17.19054) is bigger than the value of the *Critic F* (2.866266).

6.3.1.7. Summary of the comparison between the methods performance

Table 54 present a summary of the methods best performance for each category highlighted here.

Table 54 – Summary of the best performance between the four methods to the objective function cost

Feature	Small Instances	Medium Instances	Large instances
	Best method:		
less infeasible instances	equals	first and third	fourth
total less infeasible instances	fourth		
less GAP values different from zero	first, second and fourth	first, and third	first
maximum execution time	fourth	third	third
minimum execution time	third	third	third
general objective function results	first and third	first and third	first and third
general execution time results	third	third	third
average values objective function	first and third	third	third
average values execution time	third	third	third

In Table 55 that follows, we present a summary of the methods worse performance for each category highlighted here.

Table 55 – Summary of the worse performance between the four methods to the objective function cost

Feature	Small Instances	Medium Instances	Large instances
	Worse method:		
less infeasible instances	equals	second	first and third
total less infeasible instances	second		
less GAP values different from zero	second	second	second
maximum execution time	first	second	second and fourth
minimum execution time	first and second	second	Second
general objective function results	second and fourth	second and fourth	second and fourth
general execution time results	first	second	second
average values objective function	fourth	fourth	fourth
average values execution time	first	second	second

We can see by the previously analysis exposed, that in general terms the best performance in the objective function cost solution, the best performance it was of the third method, followed by the fourth method, first method and the second method at the last position.

6.3.2. Objective function *time*

6.3.2.1. Infeasible instances

In relation to the objective function time, it is possible to observe on the Tables 31, 33, 35, and 37, that the 1st method runs a total of 29 instances and two of them it was from the small instances category, fourteen from the medium instances and fifteen from the large instances, obtaining the worse result between the four methods in this sense.

The 2nd method runs a total of 45 instances and the infeasible instances it was three from the small instances category, six from the medium instances category and ix from the large instances. The 3rd method runs a total of 49 instances, being one from the small instances category, one from the medium instances and nine from the large instances category.

Finally, the 4thd method runs 56 instances and the infeasible instances it was one from the medium and three from the large instances category, obtaining the better result between the four methods analyzed in this sense. By this result it is possible to observe that the objective function time presents a higher level of difficult in comparison with objective time cost and that the proposed heuristics shows more effectiveness in this case.

6.3.2.2. Gap values

In relation to the gaps values, it is important to highlight that different of the objective cost, the results of the objective function time presented different gaps values depending of the instance category and method. To the 1st and 2nd method the values different of zero was diversified varying less to the small and medium instances, and more to the medium and to the large instances category, being close of one hundred percent in the most part of the cases. The gaps values for the 3rd and 4thd methods keeps close to zero for the major part of the instances, showing the efficiency of the LP-and-fix procedure in find good solutions. In this case the gap analysis will be more relevant.

The 1st method obtained the worse result in this sense. The overall values presented gaps values different from zero for the three instances categories. The same happened to the 2nd method. The 3rd method obtained 9 instances with gap different from zero, being 1 instance from the small category, 1 from the medium and 7 from the large instances category (the best method in this sense). The 4thd method presented 4 gaps values different from zero, being 1 from the medium category, and three 3 the large category.

6.3.2.3. Maximum and minimum values

About the maximal and minimal times obtained in the instances, it is possible to observe that the 1st and the 2nd method obtained the worse results, with 3600 seconds fort the overall instances.

The 3rd method obtained the following results: 105.05 (the best value between the four methods) and 20.93 seconds from the small instances category; 424.44 (best value) and 108.13 seconds form the medium instances; and 968, and 397.96 (the best values between the four methods) from large instances.

Finally, the 4thd method obtained the following times: 290.28 and 19.06 seconds (being 19.06 the best value) from small instances; 1179.24 and 84.42 (best value) seconds from the medium instances; and at least, 3600 (the worse value, drawing with the 2nd and 1st method) and 891.36 seconds, from the large instances category.

6.3.2.4. General terms results

In general terms of the objective function results from small instances by observing the Figure 22, we can state that the first and 3rd methods obtained results slightly better than the 2nd and 4thd methods. As in the objective function cost, it happens because when the edges structure is reduced by size reduction procedure, the algorithm now has fewer arcs to generate a result.

The same can be observed in the medium instances (with an advantage of the 2nd method in relation to the fourth, staying very close of the results from the 1st and the 3rd methods) as can be looked in Figure 24. To the large instances, the best results were obtained by the third and fourth methods. The 1st and 2nd methods stayed with results very close between themselves, with a little advantage of the second method in the sixtieth instance, but in general terms worse than two another as can be viewed at the Figure 26.

The execution time results from small instances by observing the Figure 23, we can percept that then 3rd and 4thd methods obtained the best and very similar results with a little advantage of the third method in some instances and of the fourth method in other ones. The execution times of the 1st and 2nd methods it was equals to the time limit, for the overall instances (small medium and big categories), therefore, equals, as can be viewed in Figures 23, 25 and 27.

In the execution times of the medium instances (Figure 25) the 3rd method presented a little advantage in relation to the 4th in thirtieth eighth instance. In relation to the large instances execution times (Figure 27) the 3rd method presented the best values, with the 4thd method in the second place.

6.3.2.5. Average values and standard deviation

Regarding the average values of the objective function, we can observe in the Table 38 that the 1st method obtained the best result, being followed by the 2nd method, third and so the 4thd method with the worse result. To medium instances, the previous result remained. To the large instances, the 3rd method obtained the best result, being slightly followed by the 4thd method.

The 2nd and 1st methods obtained vey worsen results, compared to the two another. Even so, the 2nd method presented a better result when compared with the first one, which obtained the worse result between the four methods. However, as in the cost case, the standard deviation values it was higher for overall instances, which characterizes a higher level of dispersion between the data values.

In Table 39 we can observe the average values related to the execution times. To the first and 2nd methods, the time limit values it was performed for the overall instances categories. In relation to the comparison between the third and 4thd methods, for the small instances, the 4thd method presented a best result. To medium and large instances, the 3rd method performed better results.

The standard deviations values of the 1st and 2nd methods do not suggest any one data dispersion for the overall instances categories. In relation to the 3rd and 4thd methods, the small instances presented a few dispersion levels, to the medium instances the dispersion it was few to the third method and moderated to the fourth, and to the large instances it was moderated to the 3rd method and high to the fourth.

6.3.2.6. Analysis of variance

About the analysis of variance for objective function values of the small instances, observing the Table 41, we can percept that the *P-value* (0.572744) it was higher than the estimated error (0.05) which means that we must accept the equality between the four samples (one for each method). We can accept this observing too that the value of *F* (0.672107) is less than the value presented in the *Critic F* (2.769431).

We can conclude the same for the execution time in Table 43 The *P-value* (0.572744) is bigger than the estimated error (0.05). Besides that, the value of *F* (0.672107) is inferior of the *Critic F* value (2.769431), so we can to accept the equality between the four samples.

Observing now the analysis of variance related to the medium instances objective function on the Table 45, the *P-value* (0.821883) is bigger than the estimated error (0.05) and the value of *F* (0.304286) is less than the value of *Critic F* (3.238872), which means that we can accept the equality between the four samples. About the medium instances execution time on Table 47, the *P-value* (1.12E-21) is less than the estimated error (0.05), and the value of *F* (2571.643) is bigger than the *Critic F* (3.238872) value, so we must refuse the equality between the four samples.

In analysis of variance to the bigger instances objective function values in the Table 49 it is important to percept that the *P-value* (0.04821) is a little bit less than the estimated error (0.05), and the value of *F* (3.281339) is a little higher than the value of *Critic F* (3.238872), which means that we must refuse the equality between the four samples. About the execution values in Table 51, it is necessary to refuse the equality between the four samples, because the *P-value* (7.97E-11) is less than the estimated error (0.05) and the value of *F* (107.8102) is bigger than the value of the *Critic F* (3.238872).

6.3.2.7. Summary of the comparison between the methods performance

Table 56 presents a summary of the methods best performance for each category highlighted here.

Table 56 – Summary of the best performance between the four methods to the objective function time

Feature	Small Instances	Medium Instances	Large Instances
	Best method:		
less infeasible instances	4th	4th and 3rd	4th
total less infeasible instances	4th		
less GAP values different from zero	3rd	4th	3rd
maximum execution time	3rd	3rd	3rd
minimum execution time	4th	4th	3rd
general objective function results	1st and 3rd	1st and 3rd	3rd and 4th
general execution time results	3rd and 4th	3rd	3rd
average values objective function	1st	1st	3rd
average values execution time	4th	3rd	3rd

In the Table 57 that follows, we present a summary of the methods worse performance for each category highlighted here.

Table 57 – Summary of the worse performance between the four methods to the objective function time

Feature	Small Instances	Medium Instances	Large Instances
	Worse method:		
less infeasible instances	1st and 2nd	1st	1st
total less infeasible instances	1st		
less GAP values different from zero	1st and 2nd	1st and 2nd	1st and 2nd
maximum execution time	1st and 2nd	1st and 2nd	1st, 2nd and 4th
minimum execution time	1st and 2nd	1st and 2nd	1st and 2nd
general objective function results	2nd and 4th	4th	1st
general execution time results	1st and 2nd	1st and 2nd	1st and 2nd
average values objective function	4th	4th	1st
average values execution time	1st and 2nd	1st and 2nd	1st and 2nd

We can conclude from the previous analysis that, in general terms, the best performance for the case of the *time* objective function, the 4th method was the best, followed by the 3rd method, 2nd method and the 1st method.

6.3.3. Analysis conclusion

Based on this comprehensive analysis, we can first conclude that the *cost* objective function is easier to handle than the *time* objective function. This happens because time seems to be more restrictive than cost.

In the *cost* objective function, the method that presented the best performance in general terms was the 3rd method (with the LP-and-fix heuristic). But when we consider the number of instances run (a possibly more important aspect), the 4th method becomes the best. It happens because the 4rd method incorporates the size reduction heuristic, which helps to reduce the number of arcs from the edges structure, decreasing the total number of arcs to be analyzed. However it comes with a cost: the quality of the solution is slightly reduced.

The "LP-and-fix" heuristic seems to be a good technique for solving the problem. This happens because when the binary decision variables are relaxed, the resulting problem becomes much easier to solve (we can observe this by looking at Tables 28, 29, 58, and 53, sub-columns III and IV, and compare the values of the relax solution and the time to the relax solution). After that, variable fixing reduces the number of arcs to be used in the solution, making the problem much easier.

The 2nd method (with the size reduction heuristic) did not present good solutions when applied to the *cost* objective function, but has a much better performance when applied to the *time* objective function, when compared to the 1st method (based on MILP). This happens because the *time* objective function increases the complexity of the problem, making it more dependent of heuristic techniques.

However, when combined with the LP-and-fix technique, the size reduction heuristic presented very good results for the *time* objective function (as seen in the 4th method). Therefore, we can conclude that in general terms, considering both objective functions, the 4th method presented the best results (followed by the 3rd method).

In terms of computational times, the size reduction heuristic presented good results for small instances, but when the number of arcs increases, the number of possible options of arcs cuts is exponential, making the computational cost higher. The LP-and-fix heuristic presented the highest efficiency in terms of computational costs, along to the value of solutions. This is, therefore, the heuristic procedure with the best performance for the multi-commodity network flow problem with time windows and multiple transport lines.

The next chapter presents the case study developed in the intercity passenger transport of the Ceará state in Brazil, in a sense to evaluate the applicability of the proposed approach to real cases.

Chapter 7

Case study

Summary: In this chapter, we describe and study a real-size case study designed around the intercity passenger transport network from the state of Ceará in Brazil. In the first section, some general information about the system under study is presented. In the second section, we describe the entities involved and the data sources, as well as the procedures used for data gathering. Then, in the third section some operational assumptions are presented, and in the fourth section, data structures and management are explained. Finally, in the fifth section we describe three test scenarios concerning the capacity of the vehicles, and in the last section, we present and analyze the results provided by the developed approaches when applied to those scenarios.

7.1. General Information

The majority of cities and towns around the world require a high volume and wide range of continuous supply of goods, to keep services in operation and to meet the ever growing needs of their inhabitants. This is especially true when dealing with basic needs. But, on the other hand, it is also known that the access to other kinds of goods and services is directly proportional to the population welfare. Therefore, the more available and the cheaper these products and services are, the higher is the quality of life.

As referred above, the central areas of large cities offer in general many advantages to their inhabitants. But unfortunately, these benefits are in general strongly associated to higher traffic congestion and pollution, which are mainly due to increasing transportation activities. These activities are obviously required to guarantee the material flows needed to supply cities, but they are directly associated to the problems caused by excessive load transport in urban environments, with pollutant emissions, intensive traffic hindering mobility in streets, high levels of noise, etc.

Therefore, any initiatives to minimize the movement of such vehicles and the cost of operating them is absolutely critical to improve city logistics, especially in larger metropolitan areas, where these problems have significantly grown in the last decades.

According to the Brazilian Institute of Geography and Statistics (in Portuguese – *Instituto Brasileiro de Geografia e Estatística* - IBGE), the state of Ceará has a geographical extension of 148,920,472 km^2 and a population of 8,842,791 inhabitants, which in practice means a large consumer market. The most populous cities are: Fortaleza, the capital, located in the state northeast with 2.591,188 inhabitants; Caucaia, Maracanaú and Maranguape, in Fortaleza's metropolitan area, with 353,932, 221,504 and 123,570 inhabitants respectively; Juazeiro do Norte, Crato and Iguatú in the south region, with 266,022, 128,680, and 101,386 inhabitants respectively; and finally, in the northwest region, Sobral and Itapipoca, with 201,756 and 124,950 inhabitants.

The intercity passenger transport in the State of Ceará is organized in eight operational areas. Each area is operated by one or more passenger transport company, providing lines that depart from the main city to the specific area. There are six transport companies operating in the state. This organization is shown in Figure 28 below.

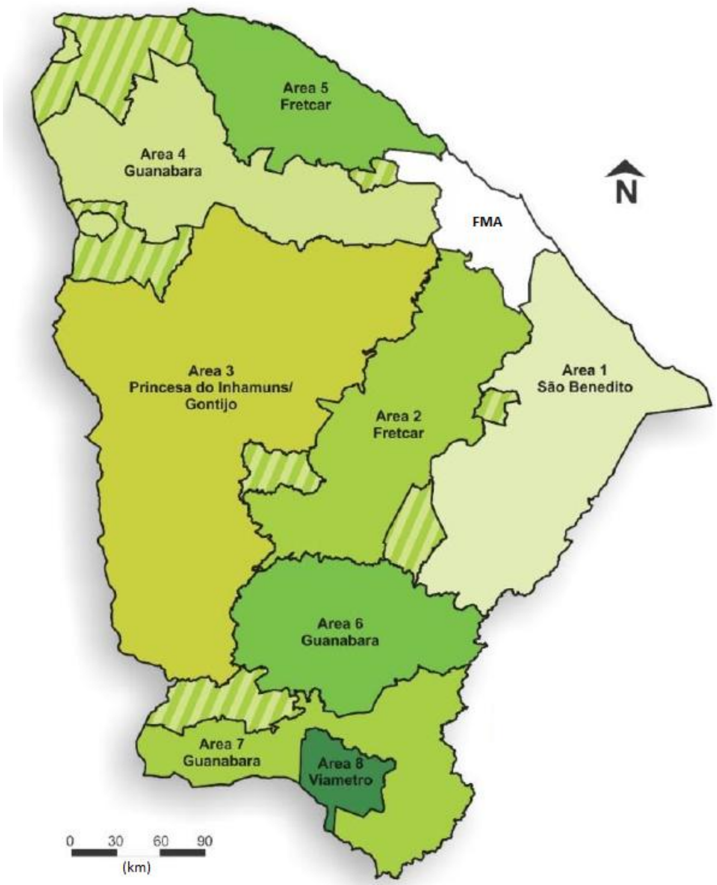


Figure 28 – Operation areas (source: ARCE, 2014).

The white area in the map represents Fortaleza metropolitan area, with all lines leaving and returning to this area. Areas 1, 2, 3, 4, 5, 6, and 7 are the basic organization for the intercity passenger's transport. Area 8 represents a rather specific metropolitan zone for passenger transport, that will not be considered in this study. The regions represented with the diagonal stripes are shared between different areas.

In the map, it is possible to observe that area 1, located in the east region of the state, is operated by the São Benedito company. Areas 2 and 5 are operated by the Fretcar company, and are located in the central and northern regions of the state, respectively. Area 3 is operated by two companies (Princesa dos Inhamuns, and Gontijo), and is located in the west region. Areas 4, 6, and 7 are operated by Guanabara, and are located in the northeast, central-south and southern regions of the state, respectively.

Table 58 provides some general information on the seven passenger transportation areas (ARCE, 2014).

Table 58 – General information about the transportation areas

Area	**Number of cities**	**Main cities**
1	25	Aracati, Russas, Morada Nova and Limoeiro do Norte
2	26	Baturité and Quixadá
3	33	Canindé, Crateús and Tauá
4	40	Sobral
5	21	Itapipoca
6	15	Iguatú
7	28	Juazeiro do Norte and Crato
Total	**188**	**13**

Each area has three different transport services in operation: conventional, executive and luxury (ARCE, 2014). The *conventional* transport service is the most common and cheapest, providing a larger number of stops, and carrying standing passengers in some cases specified by the current regulation. The *executive* service is faster, with a small number of stops, and seated passengers only. The *luxury* transport service, besides providing these benefits, is operated by vehicles with recliner beds, and therefore offers a lower passenger capacity than the others.

The data related to the total number of travels, passengers, travelled distance and transport lines by company, year and month, are presented in Tables 59, 60, and 61, for the conventional, executive and luxury services, respectively.

Table 59 - Conventional transport service

Company	Area	Travels		Passengers		Distance (km)		Transport lines
		Total (year)	Average (month)	Total (year)	Average (month)	Total (year)	Average (month)	
São Benedito	1	62,568	5,214	1,874,781	156,232	8,178,236	681,520	30
Fretcar	2	24,427	2,036	784,130	65,344	3,883,226	323,602	24
Princesa dos Inhamuns	3	26,824	2,235	902,488	75,207	7,712,350	642,696	28
Guanabara	4	21,106	1,759	672,698	56,058	5,196,167	433,014	22
Fretcar	5	33,258	2,772	1,013,332	84,444	6,997,522	583,127	26
Guanabara	6	23,131	1,928	745,539	62,128	4,505,815	375,485	8
Guanabara	7	5,999	500	197,023	16,419	2,861,722	238,477	9

Table 60 - Executive transport service

Company	Area	Travels		Passengers		Distance (km)		Transport lines
		Total (year)	Average (month)	Total (year)	Average (month)	Total (year)	Average (month)	
Fretcar	2	1,517	126	64,538	5,378	425,335	35,445	6
Princesa dos Inhamuns	3	2,582	215	80,017	6,668	904,414	75,368	5
Guanabara	4	6,785	565	240,482	20,040	1,867,017	155,585	3
Fretcar	5	5,098	425	315,612	26,301	1,667,639	138,970	8
Guanabara	6	4,022	335	137,393	11,449	1,757,032	146,419	3
Guanabara	7	6,647	554	235,279	19,607	3,609,181	300,765	3

Table 61 - Luxury transport service

Company	Area	Travels		Passengers		Distance (km)		Transport lines
		Total (year)	Average (month)	Total (year)	Average (month)	Total (year)	Average (month)	
Guanabara	4	24	2	33	396	5,520	460	24
Guanabara	6	660	55	19,656	1,368	250,536	20,878	28
Guanabara	7	4,259	355	95,895	7,991	2.307,378	192,282	22

7.2. Data Gathering

In this section, we report on how the data necessary to design the network passenger transport in the State of Ceará was obtained, and how each set of information was organized in order to fit the methodology developed in this work.

Initially, we have listed 10 categories of information which would be necessary to build the problem data structure. These categories are the following:

1. Cities list;
2. Distances matrix;

3. Vehicles schedules
4. Travel times;
5. Travel periodicity
6. Routes of transport lines
7. Total capacity of the vehicles trunk
8. Type of vehicles
9. Average of empty space on the vehicle trunks
10. Goods to be transported

The information categories listed as 1 to 6 were obtained from ARCE - Regulatory Agency of Public Services Delegates of the State of Ceará. ARCE is the agency that regulates the public transport service, having, therefore, access to overall information related to these categories.

The categories listed as 6 to 9 were obtained from the enterprise Guanabara Express. As referred, Guanabara is one of the enterprises that operate in the network passenger transport services. This enterprise was selected because it was very easy to access, and the major part of the services are operated by them. Once the service is standard for all the enterprises, the provided information can be generalized from one case to all the other cases.

The information related to the last category (10) was the only to be estimated. This happened because this kind of service is an activity that does not yet exist in practice. Moreover, the amount of products to be transported depends of the capacity of the network. Therefore, we have first determined the kind of products that would be transported, which are: non-perishable food, footwear and textile and garments. We will provide more details about these features and this choice in the next session.

7.3. Assumptions

In this section we will briefly describe the assumptions that were taken into consideration in order to adapt the real case to our modeling framework. First, we understood that it would be impossible to deal with all the 188 cities (see Table 59) because the number of arcs of the resulting problem would be intractable in computational terms (the number of possible combinations among the transport lines would be exponentially large – see the expression that computes the number of edges, in section 4.2) and many of these cities have a small population, which means that in practical terms, maybe they do not have sufficient demand.

The cities taken into consideration were the cities considered as poles inside each of the seven operation areas. This option was taken because the pole cities have in general bigger bus terminals, more inhabitants, people flow, etc. We, therefore, estimate that these cities will have a major aggregated demand for the products to be transported by the network.

Figure 29 presents the cities and poles considered inside Area 1.

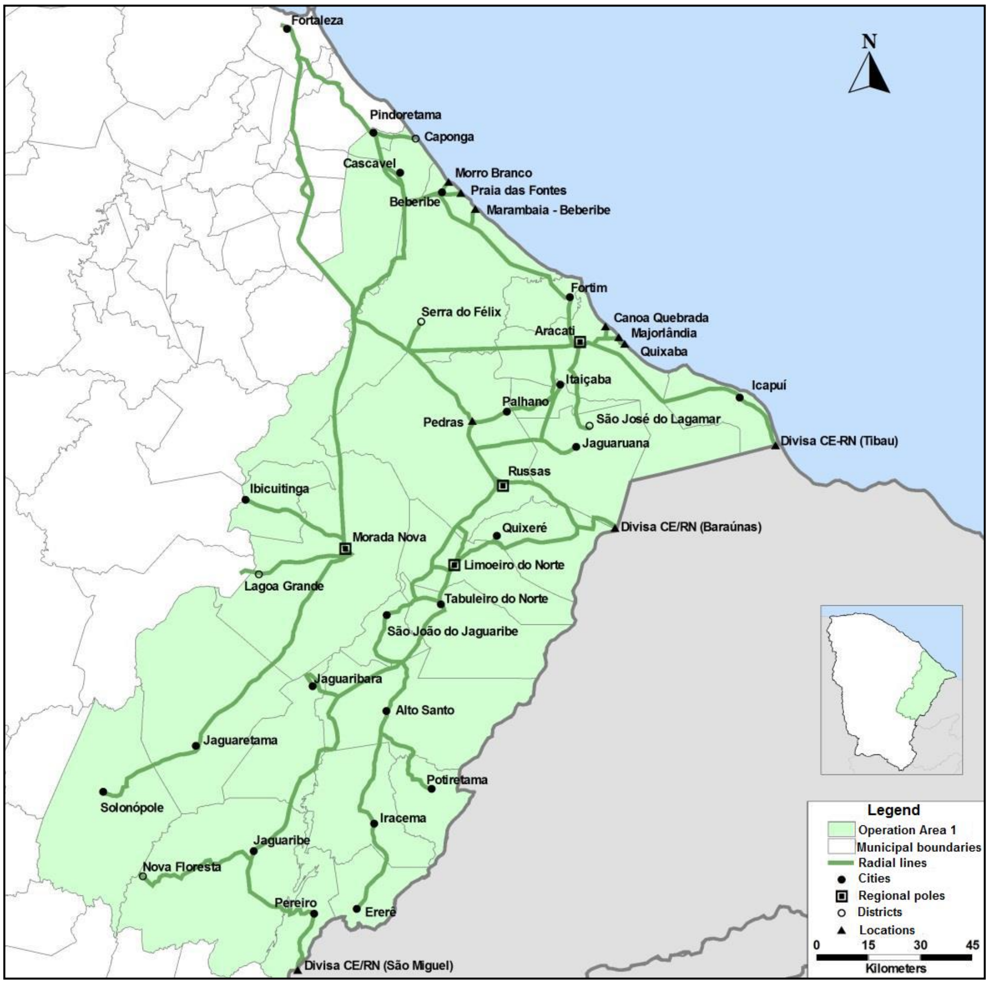


Figure 29 – Pole cities in the operation area 1 (source: ARCE, 2014)

Table 62 presents the five pole cities considered in the operation area 1 and the number of inhabitants per city, according to IBGE, 2010.

Table 62 – Pole cities from operation area 1 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Aracati	69,159
Russas	69,833
Limoeiro do Norte	56,264
Morada Nova	62,065

Figure 30 presents the cities and poles considered inside Area 2.

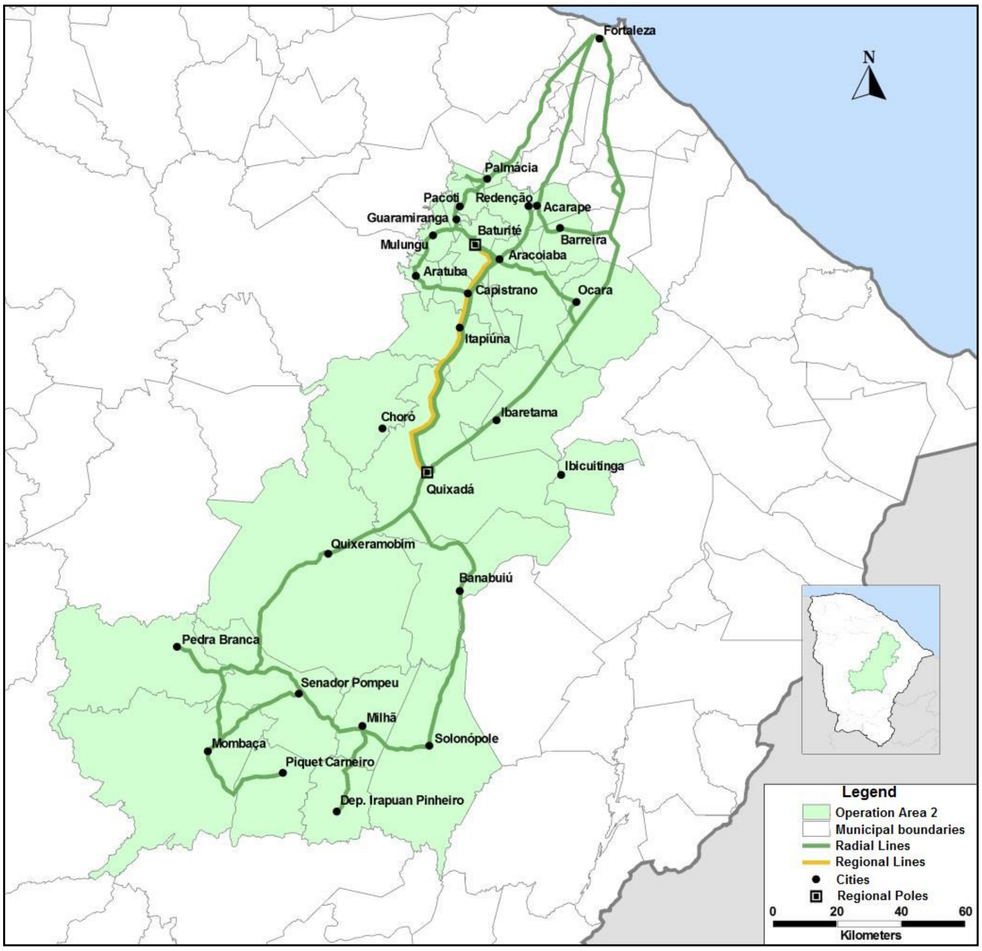


Figure 30 – Pole cities in the operation area 2 (source: ARCE, 2014)

Table 63 presents the three pole cities considered in the operation area 2 and the number of inhabitants per city, according to IBGE, 2010.

Table 63 – Pole cities from operation area 2 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Baturité	33,321
Quixadá	80,604

Figure 31 presents the cities and poles considered inside Area 3.

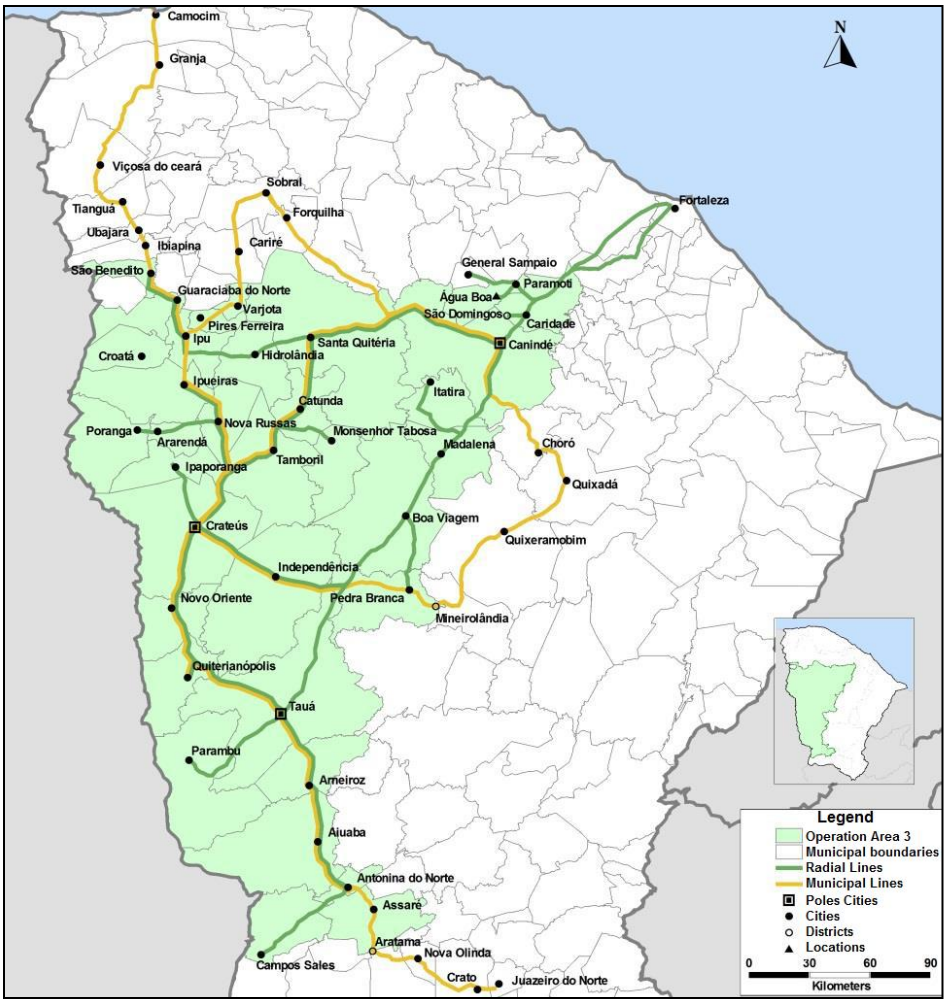


Figure 31 – Pole cities in the operation area 3 (source: ARCE, 2014)

Table 64 presents the four pole cities considered in the operation area 3 and the number of inhabitants per city, according to IBGE, 2010.

Table 64 – Pole cities from operation area 3 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Canindé	74,473
Crateús	72,812
Tauá	55,716

Figure 32 presents the cities and poles considered inside Area 4.

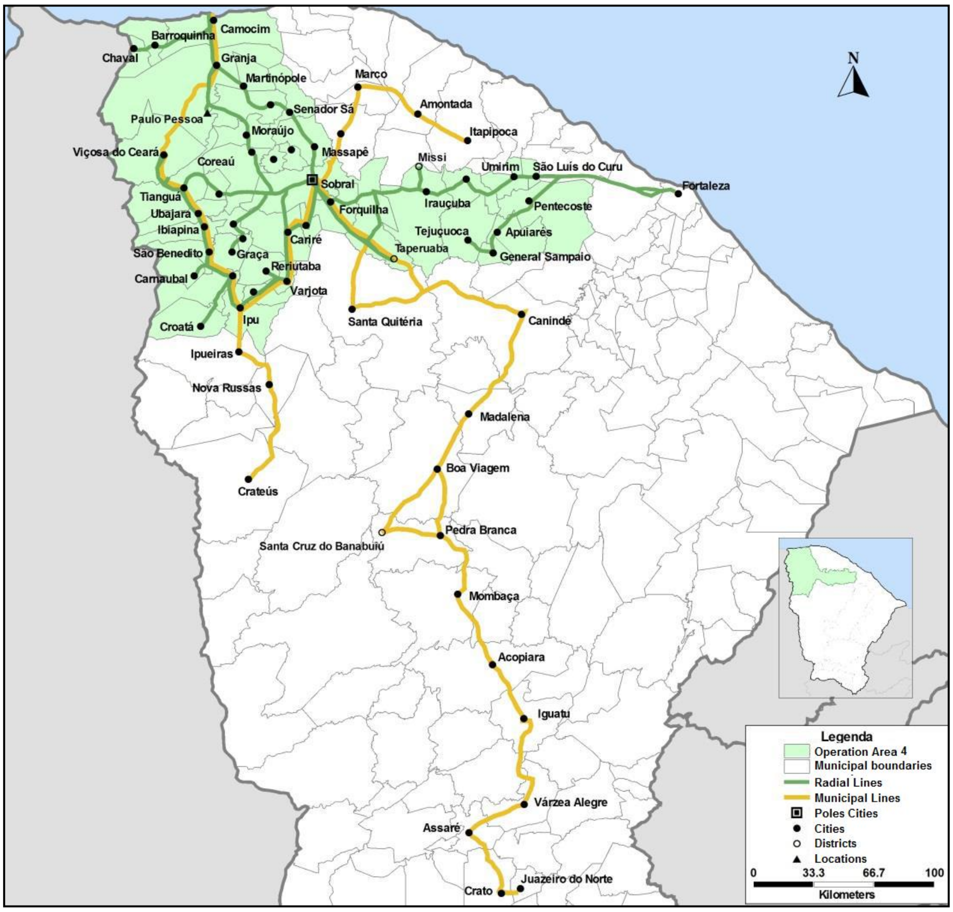


Figure 32 – Pole cities in the operation area 4 (source: ARCE, 2014)

Table 65 presents the two pole cities considered in the operation area 4 and the information related of the number of inhabitants per city, according to IBGE, 2010.

Table 65 – Pole cities from operation area 4 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Sobral	188,233

By observing Figures 31 and 32, we can see that the lines from operation area 3 cross the pole city Sobral, which is a pole highlighted in the operation area 4.

Figure 33 presents the cities and poles considered inside Area 5.

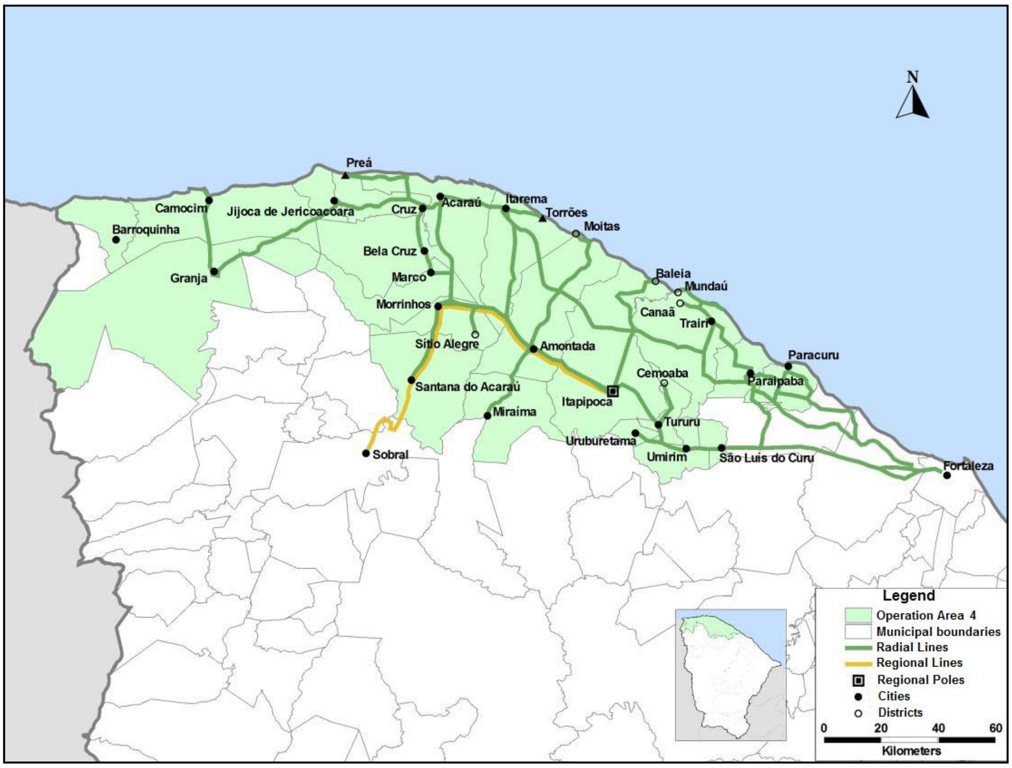


Figure 33 – Pole cities in the operation area 5 (source: ARCE, 2014)

Table 66 presents the two pole cities considered in the operation area 5 and the number of inhabitants per city, according to IBGE, 2010.

Table 66 – Pole cities from operation area 5 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Itapipoca	116,065

By looking at Figures 32 and 33, we see that the lines from operation area 4 cross the pole city Itapipoca, which is a pole highlighted in the operation area 5, and that the lines from operation area 5 cross the pole city Sobral, which is a pole highlighted in the operation area 4.

Figure 34 presents the cities and poles considered inside Area 6.

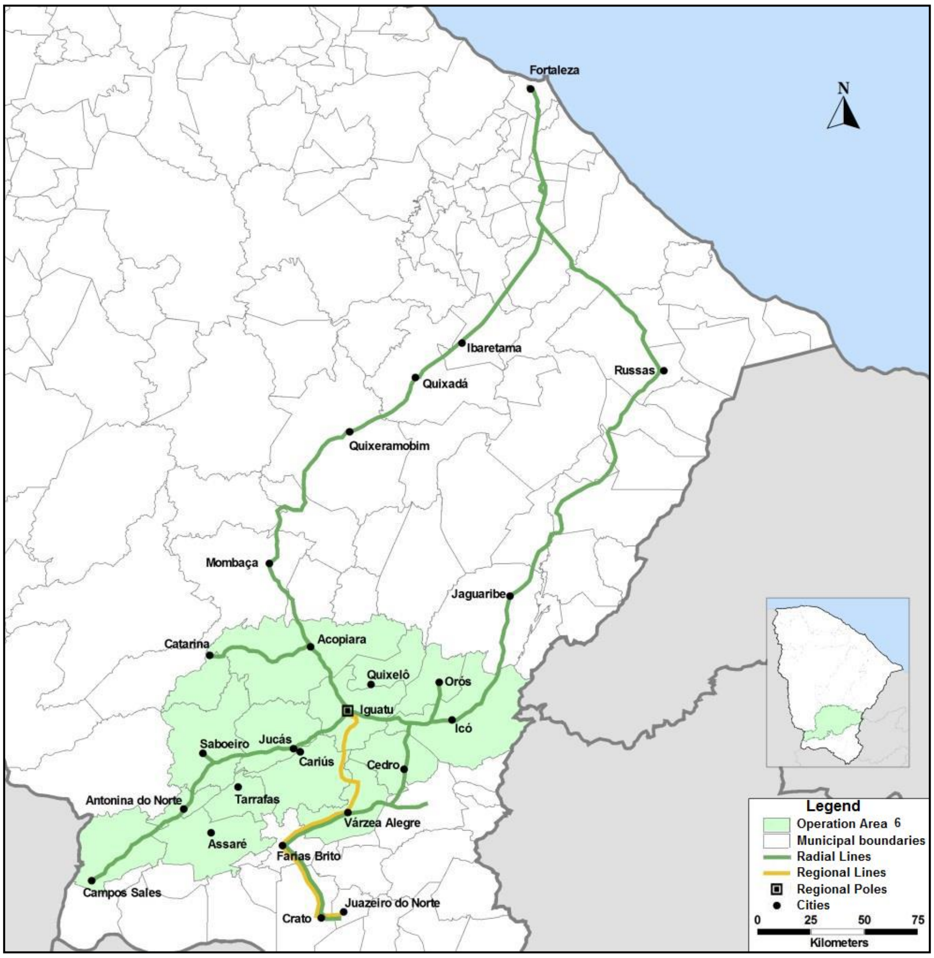


Figure 34 – Pole cities in the operation area 6 (source: ARCE, 2014)

Table 67 presents the two pole cities considered in the operation area 6 and the number of inhabitants per city, according to IBGE, 2010.

Table 67 – Pole cities from operation area 6 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Iguatu	96,495

Looking at Figures 29, 30, and 34, we can see that the lines from operation area 6 cross the pole city Russas, which is a pole highlighted in the operation area 1, and the lines from operation area 6 cross the pole city Quixadá, which is a pole highlighted in the operation area 2.

Figure 35 presents the cities and poles considered inside Area 7.

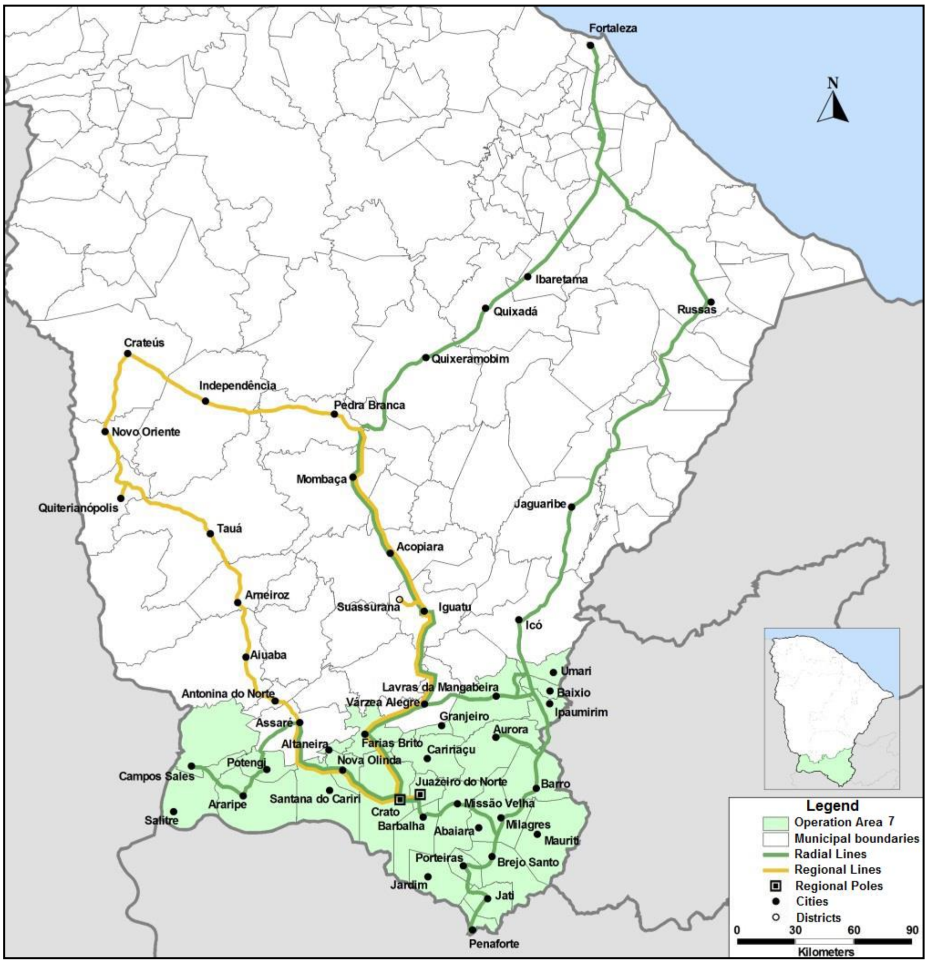


Figure 35 – Pole cities in the operation area 7 (source: ARCE, 2014)

Table 68 presents the three pole cities considered in the operation area 7 and the number of inhabitants per city, according to IBGE, 2010.

Table 68 – Pole cities from operation area 7 and number of inhabitants

Pole City	Inhabitants number
Fortaleza (state capital)	2,452,185
Juazeiro do Norte	249,939
Crato	121,428

Looking at Figures 29, 30, 31, 34, and 35, we can see that the lines from operation area 7 cross the pole city Russas, which is a pole highlighted in the operation area 1; they also cross the pole city Quixadá, which is a pole highlighted in the operation area 2; they cross Crateús, highlighted as pole from area 3; and Iguatu, from operation area 6. Note that pole cities Juazeiro do Norte and Crato are crossed by the lines from area 3 (Figure 31), area 4 (Figure 32) and area 6 (Figure 34).

Therefore, we can conclude that many pole cities are crossed by many operation areas. In fact, we have a total of 15 pole cities (including the state's capital, from where a big number of vehicles departs, linking the state capital to cities of the state interior) distributed by the seven operation areas. In order to somehow increase the number of cities visited, and to create more transshipment points, we analyzed in more detail some cities which were visited by more lines from different operation areas.

First, we realized that the cities from the operation area 5 have almost no connectivity with the other operation areas. Therefore, we selected the city of Camocim to be part of the network. This choice was made in order to include some important city (Camocim has about 60,158 inhabitants, according to IBGE, 2010) from the extreme northwest of the state, a region that had not been included. We can see that Camocim is a city included as a destination point in some lines from the operation areas 3, 4 and 5 (see figures 31, 32 and 33).

Second, we decided to include the city of Jaguaribe, that is an important city (Jaguaribe have about 34,409 inhabitants, according to IBGE, 2010) of the state´s southeast. This was a way to create more connectivity of cities from the operation area 1 with other operation areas. Jaguaribe is a city that is included as a destination point in some lines from the operation areas 1, 6, and 7 (see Figures 29, 34, and 35).

We made the decision of to include the city of Mombaça by the fact of this city be crossed by many lines of different operation areas, serving as a good transshipment point. Besides that, Mombaça is a city relatively big (with about 42,690 inhabitants, according to IBGE, 2010). Mombaça is a city that are included as a destiny point in lines from operation areas 2, 4, 6, and 7 (see the Figures 30, 32, 34, and 35).

By the same reason of the previous city, we decided to include in the network, the city of Pedra Branca, which will serve as a good transshipment point. Pedra Branca has about 41,890 inhabitants and is included as a destination point in lines from operation areas 2, 3, 4, and 7 (see the Figures 30, 31, 32, and 35).

In this way, four new cities were included in the network, increasing the total number of network nodes to 19 cities. Table 69 summarizes the cities included in the case study, presenting information as the city code (in order to facilitate the city representation inside the network), the insertion reason, and the connections of the city with the different operation areas.

Table 69 – Summary of the cities included in the case study

City	Code	Insertion reason	Connections Areas
Fortaleza	1	Pole/Transshipment	1 x 2 x 3 x 4 x 5 x 6 x 7
Aracati	2	Pole	1
Russas	3	Pole/Transshipment	1 x 6 x 7
Morada Nova	4	Pole	1
Limoeiro do Norte	5	Pole	1
Baturité	6	Pole	2
Quixadá	7	Pole/Transshipment	2 x 3 x 6 x 7
Canindé	8	Pole/Transshipment	3 x 4
Crateús	9	Pole/Transshipment	3 x 4 x 7
Tauá	10	Pole/Transshipment	3 x 7
Sobral	11	Pole/Transshipment	3 x 4 x 5
Itapipoca	12	Pole/Transshipment	4 x 5
Iguatu	13	Pole/Transshipment	4 x 6 x 7
Juazeiro do Norte	14	Pole/Transshipment	3 x 4 x 6 x 7
Crato	15	Pole/Transshipment	3 x 4 x 6 x 7
Mombaça	16	Transshipment	2 x 4 x 6 x 7
Pedra Branca	17	Transshipment	2 x 3 x 4 x 7
Camocim	18	Transshipment	3 x 4 x 5
Jaguaribe	19	Transshipment	1 x 6 x 7

In order to select the transport lines to be part of the study, we have analyzed transport lines based in the following criteria, and have selected for the case study those that

1. cross the maximum number of cites from the network;
2. have the maximum number of schedules in the working days;
3. cross at least two cities from the network;
4. have at least one schedule in the working days.

It would have been impossible to consider all the lines in all the schedules because of the exponentially large number of possible arcs, considering transshipments, as previously mentioned (see expression in section 4.2). Therefore, we decided to consider the main lines, crossing a maximum number of nodes in the network or at least two nodes, and that operate in all working days, taking the schedules as diversified as possible, but just one schedule by day and by transport line. In the next section, the selected transport lines, taking into account these criteria, will be presented.

ARCE provided us with a set of spreadsheets (one for each operation area) which were analyzed based on the previously mentioned criteria. The total numbers of lines in each operation area, classified by type of service were detailed on tables 59, 60, and 61, previously presented in section 7.1.

The times of loading, unloading and transshipment were not taken into consideration in the case study, due to the fact that the approach is new, and we cannot make a sound estimation of how long it would take to carry out such activities. However, it does not seem that those times may invalidate the solutions or the system operation.

Another assumption made was related to the capacity of the vehicles. These capacities were estimated, taking into account, the information provided by the Guanabara Express company, related to the vehicle luggage rack capacity (volume in cm^3) and to the average space of each vehicle by travel.

The vehicles' available capacities were estimated using random values between 10% and 40% of the total capacity. Each vehicle has three luggage racks, where two of them have the same measures, and another one is a little bit smaller. We have therefore computed the vehicle's luggage rack total capacity given by the sum of the total capacity of each luggage rack, as shown on Table 70.

Table 70 – Total cargo capacity by vehicle

Dimensions of the trunks by vehicle (in cm^3):					
Luggage rack number	Height (1)	Width (2)	Depth (3)	Volume (1 x 2 x 3)	Measure unit
1º	100	170	244	4.148.000	cm^3
2º	100	170	244	4.148.000	cm^3
3º	100	160	244	3.904.000	cm^3
Total capacity by vehicle:				12.200.000	cm^3

Figure 36 below shows the three luggage racks of a vehicle. The third luggage rack is the closest to the vehicle front (it is the smaller of the three racks, with capacity of 3,904,000 cubic centimeters, while the two others have 4,148,000 cubic centimeters).

Figure 36 – Luggage rack of a vehicle. (source: Expresso Guanabara)

To normalize the cargo to be transported, we used a standard box, which measures 50 centimeters of height, width, and depth, with a total capacity of 125,000 centimeters (see Table 71).

Table 71 – Standard box measures

Standard box measures (in cm^3):				
Height (1)	Width (2)	Depth (3)	Volume (1 x 2 x 3)	Measure unit
50	50	50	125,000	cm^3

Figure 37 shows the standard box used to unitize the cargo to be transported in the passenger's vehicles. This box was chosen due to its medium size. On the one hand, this box allows more flexibility in allocating cargo in vehicles with limited capacity. On the other hand, the box has not a very limited internal space, allowing the transportation of more kinds of products. As it has standard measures, this box can be obtained by the shippers easily and for a low cost.

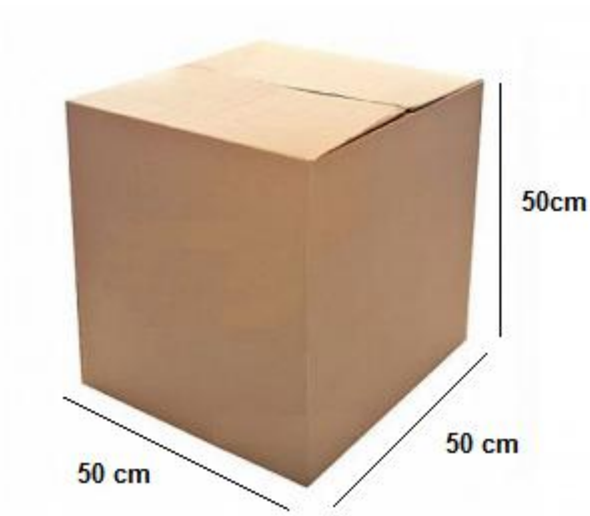


Figure 37 – Standard box (source: the author)

As the total vehicle capacity and the standard box measures are known, it is possible to estimate the average number of boxes that fit into a vehicle. In order to have an idea about this number, depending on the percentage available capacity, Table 72 shows five possible configurations. The first one was computed considering the full capacity while the others were computed considering 40%, 30%, 20%, and 10% of the total capacity.

Table 72 – Capacity estimate by vehicle

Configuration	Estimates for the vehicle capacity	Value	Measure unit
1	total number of boxes that fit in the luggage rack:	97	boxes
2	using up to 40% capacity	39	boxes
3	using up to 30% capacity	29	boxes
4	using up to 20% capacity	19	boxes
5	using up to 10% capacity	9	boxes

The value of the first configuration was calculated dividing the total capacity of the vehicle by the volume of the box. The other configuration values were calculated multiplying the value of the first configuration by a percentage. In order to consider more realistic aspects, the presented values were rounded down because the box is indivisible.

For creating the case study data, we have randomly generated these percentages (between 10% and 40%). These percentages multiplied by the value expressed in the first configuration will be plotted in the vector "*a*" from the data structure "*capacity*". The lower bounds, represented by the vector "*l*" from the data structure "*edges*" were set as 0, while the upper bounds represented by the vector "*u*," from the same data structure were set as 97 (the maximum capacity), providing more flexibility to the cargo allocation.

The previously presented values on Table 72 were useful to develop three scenarios for the case study: pessimistic, medium and optimistic. These scenarios will be discussed in detail in section 7.5.

A last assumption was considered related to offer and to demand. As previously stated, the products transported by the passenger buses must present imperishable and non-fragility features. Therefore, we choose the non-perishable food, footwear, and textile and garments.

Three cities were chosen to be "offer nodes": Fortaleza, Sobral and Juazeiro do Norte. Fortaleza was chosen to be an offer node of food because the majority of these products that come to the State of Ceará have as destination the warehouses near the capital city, to supply the big supermarket networks. Fortaleza has a good infrastructure regarding highways and warehouses. Therefore, the products that come from other states and have inland cities as destinations, could be sent first to Fortaleza and then be delivered by a low cost transport to other cities, using the passenger's transport network.

Sobral was chosen to be a footwear supplier, due to the fact that this city is the biggest production center of footwear from the State. In this way, these products could be distributed to the rest of the state by a low cost transport service.

Juazeiro do Norte, by its turn, has one of the biggest centers of textiles production. As stated for Sobral, these products can be distributed to other cities in the state by the passenger transport network at a low cost.

Twenty kinds of products were considered for our problem instances. The distribution of the products by type and supply node is presented on Table 73.

Table 73 – Products type and supplier

Type	Non-perishable food												Textile Industry					Footwear		
Products	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Supplier	Fortaleza												Juazeiro do Norte					Sobral		

The total demand of the network was estimated based on the available capacity of the vehicles. Through some preliminary tests we have verified that the system works if the total demand (positive values on the vector "*b*" in the data structure "*Vertex*") corresponds to approximately 10,4% of the total capacity of the vehicles in the "*Capacity*" structure (the total of vector "*a*").

All the other cities of the network (including the offer nodes, except for cases where they supply the product in question) are possible candidates to be "demand nodes".

7.4. Network design

This section describes how the network was designed based on the case study data and the assumptions presented in the previous section. Table 74 shows the selected transport lines, which were chosen according to the criteria mentioned in section 7.3. The itinerary was made according to the respective city codes (see table 69).

Table 74 – Selected transport lines [source: the author]

Line number	Transport Line Name	Considered itinerary		Area
		Going	Returning	
1	Fortaleza – Aracati via CE040	1-2	2-1	1
2	Fortaleza – Solonópole	1-4	4-1	
3	Fortaleza – Jaguaribe	1-3-5-19	19-5-3-1	
4	Fortaleza – Tabuleiro do Norte	1-3-5	5-3-1	
5	Fortaleza – Guaramiranga	1-6	6-1	2
6	Fortaleza – Pedra Branca	1-7-17	17-7-1	
7	Fortaleza – Mombaça – P. Carneiro	1-7-16	16-7-1	
8	Quixadá – Limoeiro do Norte	7-4-5	5-4-7	
9	Fortaleza – Pedra Branca	1-8-17-9	9-17-8-1	3
10	Fortaleza – Quiterianópolis	1-10	10-1	
11	Fortaleza – Crateús – Quiterianópolis	1-8-9	9-8-1	
12	Canindé – Quixadá	8-7	7-8	
13	Canindé – Sobral	8-11	11-8	
14	Crateús – Camocim	9-18	18-9	
15	Crateús – Sobral	9-11	11-9	
16	Fortaleza – Martinópole – Camocim	1-11-18	18-11-1	4
17	Camocim – Juazeiro do Norte	18-9-17-16-13-15-14	14-15-13-16-17-9-18	
18	Sobral – Juazeiro do Norte	11-8-17-16-13-15-14	14-15-13-16-17-8-11	
19	Itapipoca – Sobral	11-12	12-11	5
20*	Fortaleza – Jijoca de Jericoacoara	1-12	12-1	
21	Fortaleza – Iguatu via BR116	1-3-19-13	13-19-3-1	6
22	Fortaleza – Orós – Iguatu	1-7-15-14	14-15-7-1	
23	Fortaleza – Campos Sales	1-7-16-13	13-16-7-1	
24	Fortaleza – Cedro – Limoeiro do Norte	1-3-5-19-15-14	14-15-19-5-3-1	
25	Fortaleza – Juazeiro do Norte	1-7-16-13-15-14	14-15-13-16-7-1	7
26	Juazeiro do Norte – Tauá	14-15-10-9	9-10-15-14	

As previously stated (section 7.3), we have considered one schedule for all the transport lines in the workdays, and therefore we have five vehicles by transport line (one per day). Each vehicle goes to the destination point and returns to the origin point.

Figure 38 presents the graph resulting from the developed network.

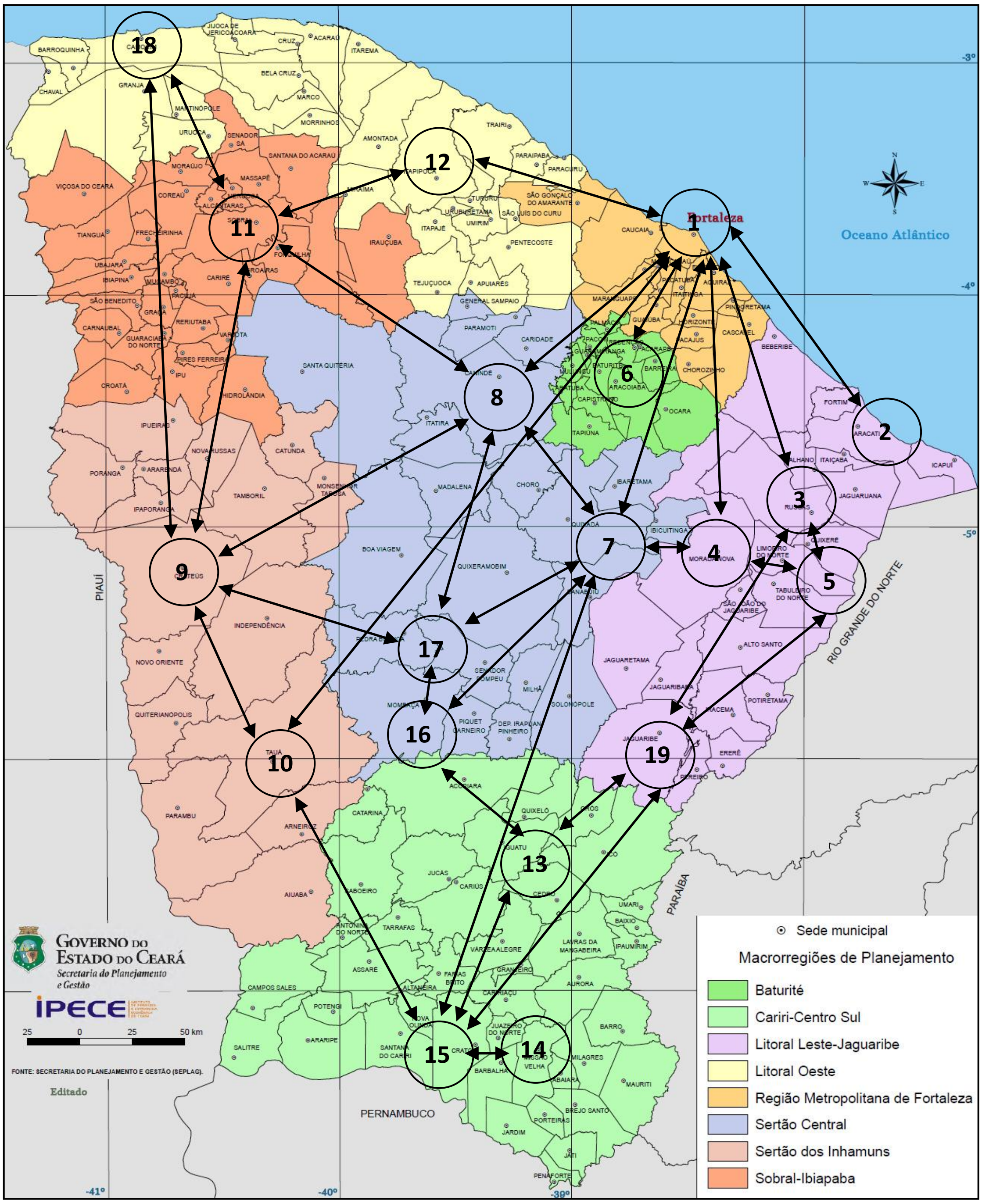


Figure 38 – Network graph (source: adapted from IPECE, 2018)

The different data structures have been filled gradually, and following the same logic of the algorithm used for the instances generator (see section 6.1): *edges*, *capacity* and *vertex* (see table 75).

Table 75 – Data structures

Edges		*Capacity*		*Vertex*	
Vector	Meaning	Vector	Meaning	Vector	Meaning
t	Origin transport line	t	Transport line	k	Product Type
o	Destiny transport line	v	Vehicle	i	Node
v	Origin vehicle	i	Origin node	b	Offer/Demand
q	Destiny vehicle	j	Destiny node	-	-
k	Product type	a	Capacity	-	-
i	Origin node	-	-	-	-
j	Destiny node	-	-	-	-
c	Cost (distance)	-	-	-	-
l	Lower bound capacity	-	-	-	-
u	Upper bound capacity	-	-	-	-
p	Departure time	-	-	-	-
h	Travel time	-	-	-	-
d	Arrive time	-	-	-	-

The data structure *edges* was developed for the case study, vector by vector. We started with all the arcs related to each vehicle trip, filing the vectors *t*, *o*, *v*, *q*, *i* and *j*, associated with the direct routes, without transshipment. Then, we have filled the vectors c (with the corresponding distances between nodes *i* and *j*), *p*, *h*, *d* (with the corresponding values for departure, travel and arrival times). And finally, we have replicated the generated vectors for each product, filling the vector *k*.

After this step, we characterized the transshipment arcs, combining all the routes with connection possibilities. To identify these possibilities, we have checked if node *j* of the arc corresponding to the origin transport line and its vehicle was equal to the node *i* from the arc corresponding to the destination transport line and vehicle. This procedure was repeated for all the possible combinations. In this way, vectors *t*, *o*, *v*, *q* are filled according to the origin/destination transport line and vehicle, while *i* and *j* are defined considering the nodes *i* and *j* from the destination arc, as the freight will follow this flow. Therefore, the values of *c* and *h* for each transshipment arc come from the destination line, corresponding to the distance and travel duration, respectively, of the arc *i* and *j*. The value of *p* to the transshipment arc were computed taking the value of *d* from the origin arc. The value of *d* to the transshipment arc is equal to the value of *d* from the destination arc. We have then replicated the generated vectors for each product, filling the vector *k*.

Finally, vectors *u* and *l* were filled (considering direct and transshipment routes) following the guidelines from the previous section.

The data structure *capacity* was developed taking the values of each vehicle individually, and its corresponding pair of nodes and transport line, thus filling the values of *t*, *v*, *i* and *j*. Then, the capacity of the vehicle was computed according to the scenario (see the previous section).

Finally, the data structure *vertex* was developed by listing all the products and their related offer/demand nodes. In this way, we have filled vectors *k* and *i*, respectively. Then, vector *b* was filled as proposed in the previous section.

As proposed in section 6, we have created for the case study, a secondary data structure named *demand*, following the same principles used in the random generation of the test instances (in order to better deal with constraints (6) of the model).

See table 76 for the main characteristics of the network of the case study.

Table 76 – Features of the case study network

Feature	Amount
Transport lines	26
Product types	20
Vehicles	130
Arcs	215.715

7.5. Scenarios

In order to better explore the case study, three scenarios were designed. These scenarios were developed varying the capacities of the vehicles, as stated in Table 71 (first configuration), see Section 7.3.

The first scenario is "pessimistic", considering between 10% and 40% of the total destination vehicle capacity. The second case is the "medium" scenario, with a vehicle's capacity between 20% and 40%, while the "optimistic" scenario considers values between 30% and 40%.

As previously stated, all the scenarios were generated randomly, using uniform distributions (with the total vehicle capacity being the first configuration on Table 71). The resulting values were used in vector *a* of the sub-structure *capacity*.

7.6. Case study results and discussion

A total of 24 tests were performed. These tests are the different combinations of the 2 objective functions, the 4 different methods, and the 3 scenarios described above. The results of these tests are presented in this section.

7.6.1. Objective function *cost*

Table 77 presents the results for the *cost* objective function, in the case study.

Table 77 – Case study results for the *cost* objective function

Scenario	Feature	1st method	2nd method	3rd method	4th method
Pessimistic	Objective value	261990	261990	261990	261990
	Execution time	177.835	192.845	48.323	58.086
	Gap	0%	0%	0%	0%
Medium	Objective value	258681	258686	258681	258681
	Execution time	175.601	178.993	43.52	66.101
	Gap	0%	0.18%	0%	0%
Optimistic	Objective value	258293	258293	258293	258293
	Execution time	178.344	171.174	36.127	56.13
	Gap	0%	0%	0%	0%

Table 78 presents the values related to the total time reduction from the 2nd and 4th methods, relax objective solution and total time relax solution from the 3rd and 4th methods.

Table 78 – Additional values of the heuristics results for the objective function cost

Scenario	Feature	2nd method	3rd method	4th method
Pessimistic	Total time reduction	31	-	31
	Relax Obj solution	-	261990	261990
	Total Time Relax solution	-	26.3	17
Medium	Total time reduction	31	-	31
	Relax Obj solution	-	258681	258681
	Total Time Relax solution	-	25	17.2
Optimistic	Total time reduction	31	-	31
	Relax Obj solution	-	258293	258293
	Total Time Relax solution	-	22.2	14.1

Based on the presented results it is possible to conclude that all the methods provided the optimal solution, except the 2nd method in the medium scenario, which provided an almost the optimal result, with a gap about zero point eighteen percent — the main difference between the methods it was in the execution times. The best results were presented by the 3rd method, being followed by the 4th method. The 1st method it was better than the 2nd at the pessimistic and medium scenarios, but worse in the optimistic scenario.

Figure 39 presents the execution time results for the four methods and the three scenarios.

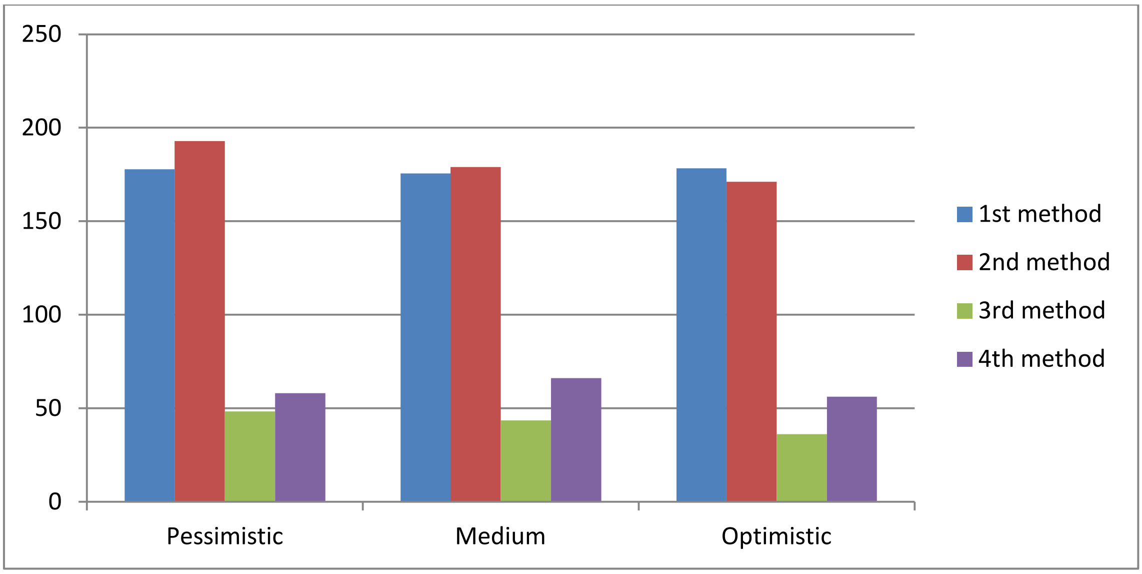


Figure 39 – Execution time results for the objective function cost

It is possible to conclude that for the objective function cost, the methods presented similar results regarding gap and objective function value, but regarding execution time, there was a significant difference especially between the two first methods and the two at last. Table 79 presents the average and standard deviation values from the four methods execution times.

Table 79 – Average and standard deviation for execution times in objective function cost

Statistical Measure	1st method	2nd method	3rd method	4th method
Average	177	181	43	60
Standard Deviation	1.46	10.976	6.14	5.28

Table 80 presents the difference between the average values provided by the four methods. Reading the lines from Table 81, the positive values indicate that the method was worse in the comparison, while the negative indicates bigger efficiency.

Table 80 – Difference between execution times of the objective function cost

Methods	1st	2nd	3rd	4th
1st	0	-4	134	117
2nd	4	0	138	121
3rd	-134	-138	0	-17
4th	-117	-121	17	0

Comparing the differences of the average values from the four methods, it is possible to percept that the biggest difference is between the 2nd and the 3rd methods (about one hundred thirty-eight), and the smallest difference is between the 1st and the 2nd.

The numbers showed on Table 78 allows concluding that the 3rd and 4th methods presented the best results and similar between each other, which testifies the efficiency of the heuristic LP-and-fix (present in the two methods) in solving this problem. The heuristic size reduction was not efficient in this sense, but when combined with the LP-and-fix (4th method), presented good results.

The standard deviation values allow concluding that the method which presented less variation between the results related to execution times from the three scenarios, it was the 1st method, being followed by the 4th, 3rd and at last the 2nd.

If we observe the results presented in Table 79, it is possible to see that the size reduction heuristic it was not inefficient regarding time, performing the value of thirty-one 2nds for the overall scenarios on the 2nd and 4th methods.

7.6.2. Objective function *time*

Table 81 shows the results for the *time* objective function.

Table 81 – Case study results for the objective function time

Scenario	Feature	1st method	2nd method	3rd method	4th method
Pessimistic	Objective value	0	0	86589	95699
	Execution time	3600	3600	74.417	84.18
	Gap	0%	0%	0%	0%
Medium	Objective value	0	0	80499	81640
	Execution time	3600	3600	78.091	91.766
	Gap	0%	0%	0%	0%
Optimistic	Objective value	75127	78076	75359	78279
	Execution time	3600	3600	60.187	83.714
	Gap	0.62%	0.57%	0%	0%

Table 82 presents the values related to the total time reduction from the 2nd and 4th methods, relax objective solution and total time relax solution from the 3rd and 4th methods.

Table 82 – Additional values of the heuristics results for the objective function time

Scenario	Feature	2nd method	3rd method	4th method
Pessimistic	Total time reduction	-	-	31
	Relax Obj solution	-	1299.28	1349.58
	Total Time Relax solution	-	50	32
Medium	Total time reduction		-	31
	Relax Obj solution	-	1248.58	1296
	Total Time Relax solution	-	51	35
Optimistic	Total time reduction	31	-	31
	Relax Obj solution	-	1218.4	1233.78
	Total Time Relax solution	-	40	33

From the results presented for the *time* objective function, we can conclude that just the 3rd and 4th methods provided the optimal solution in all the scenarios. 1st and 2nd methods did not produce solutions for the pessimistic and medium scenarios. There were differences between the objective function values, execution times and two different gaps different from zero for 1st and 2nd methods, but it should be highlighted that these gaps were almost zero. Similarly to the *cost* objective function, the best results were produced by 3rd method. 1st method was better (in terms of objective value) than 2nd method, for the optimistic scenario, but worse in terms of the gap value This means that the result was further from the optimal solution than the result obtained by 2nd method.

Figure 40 presents the objective function value results for the four methods and the three scenarios.

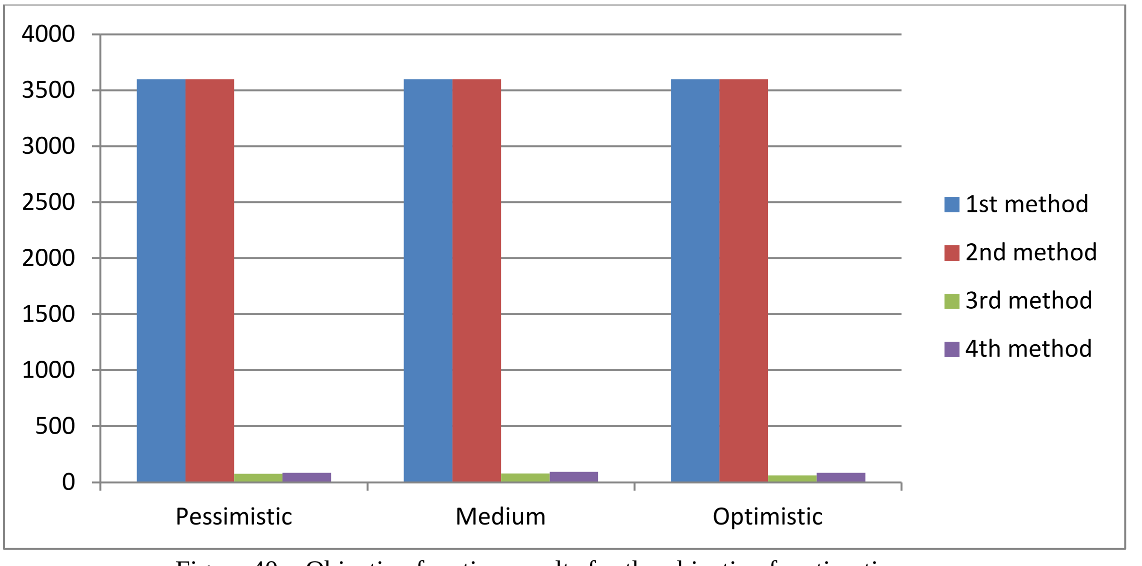


Figure 40 – Objective function results for the objective function time

Figure 41 presents the execution time results for the four methods and the three scenarios.

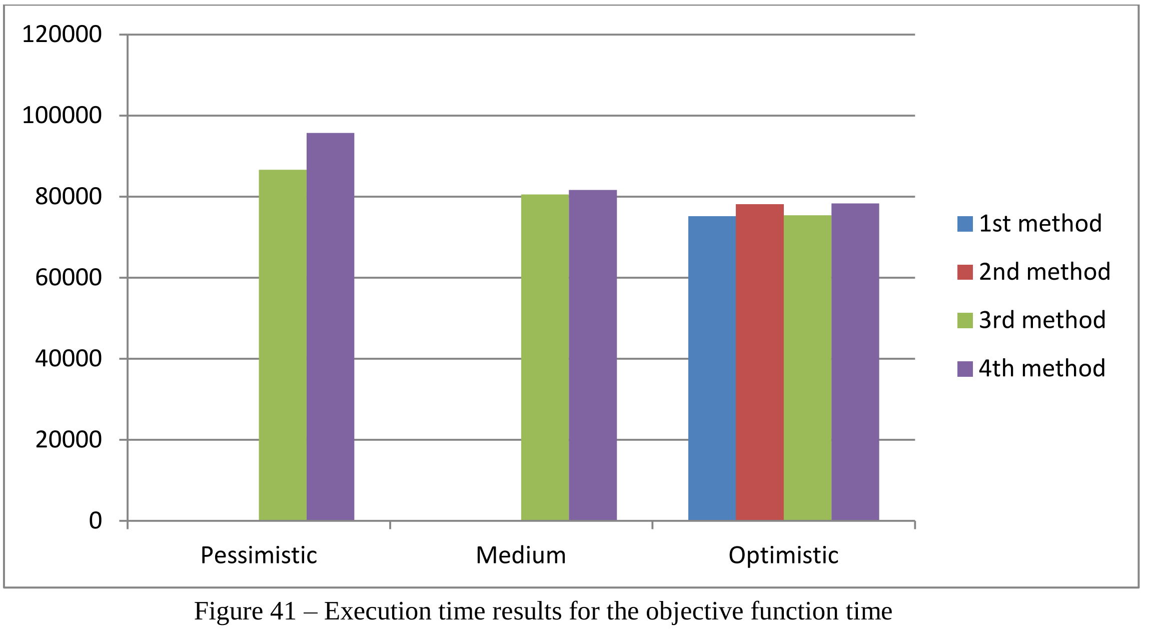


Figure 41 – Execution time results for the objective function time

It is possible to conclude that for the objective function time, the methods presented similar results regarding gap and objective function value, but regarding execution time, there was a significant difference especially between the two first methods in one hand, and the two at last in another hand. Table 83 presents the average and standard deviation values from the four methods objective values, while Table 84 shows the same values for the execution times.

Table 83 – Average and standard deviation for objective values in objective function time

Statistical Measure	1st method	2nd method	3rd method	4th method
Average	*	*	80815.67	85206
Standard Deviation	*	*	5621.69	9241.29

*impossible evaluate because the method does not produce results for the overall instances.

Table 84 – Average and standard deviation for execution times in objective function time

Statistical Measure	1st method	2nd method	3rd method	4th method
Average	*	*	70.90	86.55
Standard Deviation	*	*	9.46	4.52

*impossible evaluate because the method does not produce results for the overall instances.

Table 85 presents the difference between the values presented by the four methods for the objective value and optimistic scenario (where all the methods found results), while Table 86 shows the same values for the execution times. In the reading of the lines from Tables 85 and 86, the positive values indicate that the method was worse in the comparison, while the negative indicates bigger efficiency.

Table 85 – Difference between objective values of the objective function time

Methods	1st	2nd	3rd	4th
1st	0	-2.949	-232	-3.152
2nd	2.949	0	2.717	-203
3rd	232	-2.717	0	-2.920
4th	3.152	203	2.920	0

Table 86 – Difference between execution times of the objective function time

Methods	1st	2nd	3rd	4th
1st	0	0	3.540	3.516
2nd	0	0	3.540	3.516
3rd	-3.540	-3.540	0	-24
4th	-3.516	-3.516	24	0

Comparing the differences of the objective function values from the four methods on Table 85, it is possible to conclude that the biggest difference is between the 1st and the 4th because the 1st method does not use heuristic techniques and the 4th combines both. Comparing the heuristics regarding efficiency, we can get to conclude that the LP-and-fix it was better than size reduction as regarding solution quality, as in computational time for an instance of this size applied in the time objective function. The smallest difference it was between the 2nd and the 4th methods, proving that, in this context, the size reduction heuristic contributes to decrease the quality of the solution, when compared with the LP-and-fix heuristic.

The numbers shown on Table 87 allow us to conclude that the 3rd and 4th methods present the best (and similar) results, this showing the efficiency of the LP-and-fix heuristic (present in the two methods) in solving problems of this size. Moreover, the size reduction heuristic does not present a high computational time.

The standard deviation values allow concluding that the method which presented less variation between the results related to objective function it was the 3rd (in comparison to the 4th method, once the other ones do not produce results for overall instances). About the execution times from the three scenarios, the minor variation it was obtained by the 4th method (in comparison to the 3rd method). Therefore, the results allow concluding that for the objective function time the size reduction heuristic contributes to decrease the variation of execution time, while the LP-and-fix reduce the variation related to objective function value, considering all the three scenarios.

By the number of arcs, we can to conclude that the case study is a medium size instance. For these kinds of instances, there is no doubt that the best cost-benefit is the 3rd method, being followed by the 4th, 1st, and 2nd, on this ordering. This occurs because the size reduction heuristic shows itself better solving large instances.

However, the size reduction heuristic it was not bad regarding efficiency when we observe the execution times presented in Table 83. The proceeding presented a good execution time about 31 seconds for the optimistic scenarios on the second method and the same time when combined with LP-and-fix heuristic on the 4th method. In this last approach, the heuristic presented good results.

The next chapter presents the final considerations and conclusions of this doctoral thesis.

Chapter 8

Conclusion

Summary: The main goal of this thesis was to contribute for the design of a new freight delivery system, based on an intercity passenger transport network, and aiming to enhance the performance of the different stakeholders. The problem was modeled by extending similar models from the literature, and specific resolution heuristic techniques were developed. Given the innovative nature of our approach, we developed representative test instances in order to assess the efficiency and effectiveness of the proposed techniques and to show their potential in supporting decision-making. In this section we present the main conclusions and achievements of this work, as well as some suggestions for future research.

8.1. Main achievements and contributions

In this section, the main contributions of this work are presented by topics directly associated to the specific objectives of the doctoral project, as established in the introduction of the thesis.

- We have developed an approach aiming to integrate the passenger transport system and urban freight. The proposed approach involves decisions at different levels, with relevant strategic, tactic and operational issues. In general terms, this system addresses the needs of the different involved stakeholders: the shippers and carriers, who expect a decrease of the transport costs, by using a transport that already goes to the required destinations, independently of having freight or not; and citizens and authorities, with a decrease of the traffic levels, and with less noise, visual and environmental pollution. We believe that this goal was achieved.

- We developed a new, effective mathematical model for the problem. This model was developed based on the traditional multi-commodity network flow problem. Some adaptations were undertaken in order to adapt it to the problem specific features, such as multiple suppliers and customers, multi-transport lines, multiple vehicles, and complex time schedules. The resulting model is a multi-commodity network flow problem with multi-transport lines, multiple vehicles, and time windows. In this context, we developed two objective functions, the first one related to *cost* and the second to *time*. We believe that this is a relevant contribution to the operations research literature, since no other researchers had already explored this specific problem.
- For this new problem we have proposed some heuristic approaches, having developed an instances generator, and with this generator we have created a set of instances of various sizes to test those heuristics (size reduction and LP-and-fix heuristics, and a combined approach). For comparison purposes, another approach was developed using an optimization software (CPLEX). Individually the size reduction heuristic presented quite good results, especially for large instances. The LP-and-fix heuristic applied individually worked quite well in what concerns *time* and *cost*. The two heuristics, when combined, presented the best results for the two objective functions.
- Finally, in order to test the applicability of the approach in a real context, we developed a case study based on the Ceará state intercity passenger transport, and using real data. Some assumptions were made in order to adapt and simplify a complex reality, thus creating an adequate setting to test and assess the developed approaches. The LP-and-fix heuristic presented the best results in the case study, followed by the hybrid method.

8.2. Conclusions

In general terms, we can conclude that the overall objectives of this doctoral project have been achieved. As demonstrated throughout the work, we could show that the proposed approach is capable of efficiently integrating urban freight with the intercity passenger network. The model and its resolution methods presented good, quite promising results, when applied both to randomly generated problem instances and to the case study.

We therefore believe that this model can be applied in practice in real contexts, thus contributing to the generation of measurable and non-tangible benefits. A potential decrease of the traffic congestion is one of these benefits. By exploring the developed approach, we could conclude that, in the case study, a total of 1600 boxes of products could be delivered just considering a few transport lines and vehicles. Therefore, about four urban cargo vehicles can be out of the roads every week (if the vehicles are truck wagons, this would mean one vehicle per week). Extending the approach and further exploring the network capacity, many other vehicles can be out of operation. This will significantly contribute to a high reduction of traffic congestion and other negative environmental effects generated by the vehicles.

The decrease of transportation costs is another clear benefit provided by our approach. As vehicles run independently of the allocated freight, the service will have quite competitive costs in cargo transportation.

However, one weakness (limitation) of the model is the need of very complex data structures. The high number of "indices" increased the number of possibilities a lot, especially on the "edges" data structure. We, therefore, concluded that it would be particularly difficult to develop a heuristic / metaheuristic approach to deal directly with the problem (as modeled), without the use of an optimization tool.

Moreover, some assumptions made for the case study were probably quite strong, in particular in the simple way the available capacity of the vehicles was computed. In another direction, the demand might be estimated using other techniques, such as statistical approaches, in order to make results more realistic.

8.3. Suggestions for future work

Our experience with this research project naturally generated several ideas and guidelines for future work in this domain:

- since the problem studied in this thesis is a new variant of the multi-commodity network flow problem, an important additional contribution would be to apply other heuristics / metaheuristics to the resolution of the model;
- to develop a multi-objective approach, integrating the objective functions *cost* and *time*, in order to find trade-off, practically interesting solutions;
- another important contribution would be to apply some variant of the tridimensional bin packing problem to optimize the use of the vehicles' baggage pack;
- to create a decision support system to integrate the information related to urban freight origins / destinations, thus improving network management;
- a key point to be addressed is the estimation of vehicle and line effective capacity, taking into account the average space capacity along the time horizon (considering peak or normal capacity periods) and the total number of vehicles in each line (naturally, in peak hours, vehicles will have a smaller available load capacity, and in off-peak hours, a larger capacity); the estimation of these capacities should be established based on field studies, and should be subsequently adjusted to guarantee reasonable measurement errors; a discrete event simulation could be used to reduce the uncertainty related to these measures and to validate the results generated by the optimization model;

- to study larger problems, with more transport lines and vehicles, in order to evaluate the total delivery capacity of the system;
- to allocate other items that can be transported by the intercity passenger transport network system;
- to apply the model to other modes of transport as trains or airplanes;
- to apply this approach to other contexts, such as interstates and inter-countries passenger transport systems.

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