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Everton da Silveira Farias

A HEURISTIC APPROACH TO SUPPLY CHAIN NETWORK DESIGN IN A MULTI-COMMODITY FOUR-ECHELON LOGISTICS SYSTEM

Porto Alegre – RS

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Thesis presented in partial fulfillment
of the requirements for degree of
Doctor of Administration
Advisor: Prof. Ph.D. Denis Borenstein

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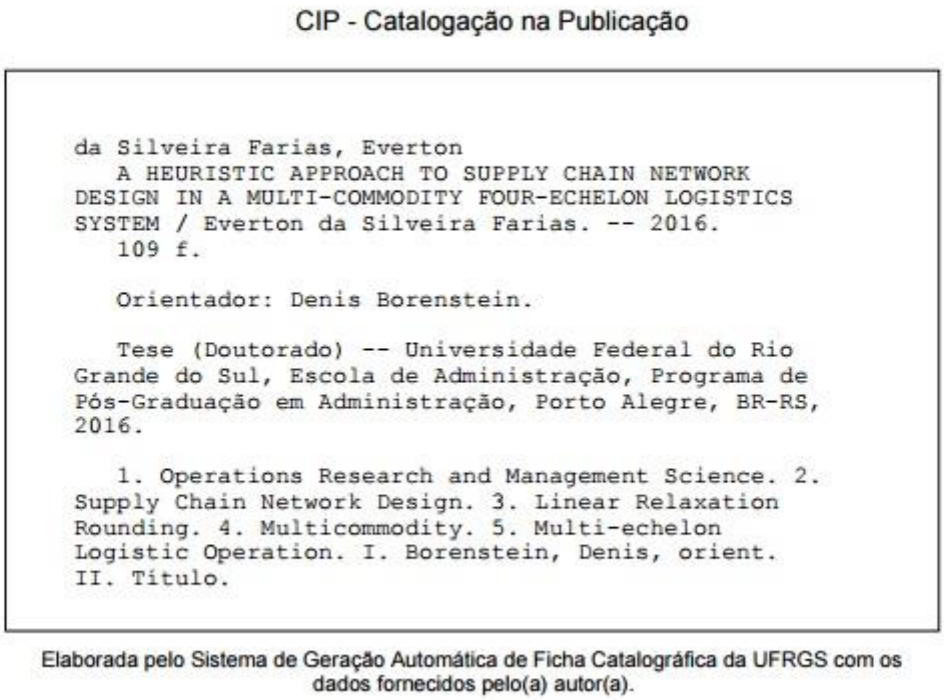

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This thesis has analyzed and judged adequate for obtaining the Doctor's degree in Administration and approved in final form by the Advisor and the evaluation committee designated by the Post-Graduation in School of Management from the Federal University of Rio Grande do Sul.

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To my wife Gabriela.
My parents Loureno (in memoriam) and Regina.
My brother Anderson and my sister Aline.
To my beloved nephews and
to someone beloved who is coming.

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“Loaded like a freight train
Flyin' like an aeroplane”

Nightrain by Guns N’ Roses

ABSTRACT

In this thesis we propose a heuristic method for the Supply Chain Network Design (SCND) problem considering several aspects of practical relevance: suppliers and raw materials, location and operation facilities, distribution center (DC) assignments, and large numbers of customers and products. An efficient two-phase heuristic approach is proposed for obtaining feasible solutions to the problems, which is initially modeled as a large-scale Mixed Integer Linear Program (MILP). In the construction phase, a linear programming rounding strategy is applied to obtain initial values for the integer location variables in the model. Simultaneously, a Multi-start method was developed to generate diversified initial solutions from each new iteration in the rounding heuristic. In the second phase, two Local Search procedures were developed towards to improve the solution provided by the rounding method. We implemented two different Local Search approaches: removal-insertion and exchange. A Tabu Search technique was developed to guide the Local Search procedure to explore the different spaces of solutions. The formulations and algorithms were implemented in C++ code language using the optimization engine COIN-OR. The solution method was experimented in randomly generated instances, with different sizes in terms of the number of parameters, such as number of products, customer zones, DCs, and factories considering a four-echelon logistic system. The computational implementations show that the solution method proposed obtained satisfactory results when compared to the literature review. To validate this heuristic method was also used in a realistic case, based on data from a rubber company that is restructuring its supply chain due to the overture of a new factory, producing new products. The proposed heuristic approach proved appropriate to practical application in a realistic case of a multi commodity industry in a deterministic context.

Keywords: Operations Research and Management Science, Supply Chain Network Design, Linear Relaxation Rounding, Local Search, Multicommodity, Multi-echelon Logistic Operation

RESUMO

Nesta tese propõe-se um método heurístico para o problema de Projeto de Rede da Cadeia de Suprimentos (Supply Chain Network Design) considerando vários aspectos de relevância prática, tais como: fornecedores e matérias-primas, localização e operação de instalações, atribuição de Centros de Distribuição (CD), e grande número de clientes e produtos. Uma eficiente abordagem heurística de duas fases é proposta para a obtenção de soluções viáveis para os problemas, que inicialmente é modelado como um Programa Linear Inteiro Misto (PLIM) de grande escala. Na fase de construção, uma estratégia de Linear Programming Rounding é aplicada para se obter os valores iniciais para as variáveis de localização inteira do modelo. Simultaneamente, um método Multi-start foi desenvolvido para gerar soluções iniciais diversificadas para cada nova iteração da heurística de Rounding. Na segunda fase, dois procedimentos de Busca Local foram desenvolvidos no sentido de melhorar a solução fornecida pelo método de Rounding. Implementamos duas diferentes abordagens de Busca Local: remoção-inserção e troca. Uma técnica de Busca Tabu para orientar o procedimento de Busca Local para explorar os diferentes espaços de soluções foi desenvolvida. As formulações e algoritmos foram implementados na linguagem C++ utilizando ferramentas de otimização da COIN-OR. O método de solução foi experimentado em instâncias geradas aleatoriamente, com tamanhos diferentes em termos do número de parâmetros, tais como o número de produtos, zonas de clientes, CDs e fábricas considerando um sistema logístico de quatro níveis. As implementações computacionais mostram que o método de solução proposto obteve resultados satisfatórios quando comparados com a literatura. Para validar este método heurístico também foi usado em um caso realista, com base em dados de uma empresa de borracha que está reestruturando sua cadeia de suprimentos devido ao projeto de uma nova uma nova fábrica e produção de novos produtos. A abordagem heurística proposta revelou-se adequada para aplicação prática em um caso real de uma indústria multicommodity em um contexto determinístico.

Palavras-chave: Pesquisa Operacional, Projeto de Rede da Cadeia de Suprimentos, Relaxamento Linear Rounding, Busca Local, Multi-commodity, Operação Logística de Múltiplos Níveis

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LIST OF ABBREVIATIONS AND ACRONYMS

CFLP	Capacitated Facility Location Problem
CFLPSS	Capacitated Facility Location Problem Single Source
COIN-OR	Computational Infrastructure for Operations Research
BD	Bender Decomposition
DC	Distribution Center
FLP	Facility Location Problems
GA	Genetic Algorithm
LB	Lower Bound
LP	Linear Programming
LS	Local Search
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Problem
MUFLP	Multiproduct Uncapacitated Facility Location Problem
PDSDP	Production Distribution System Design Problems
SC	Supply Chain
SCM	Supply Chain Management
SCND	Supply Chain Network Design
TS	Tabu Search
UB	Upper Bound
UFLP	Uncapacitated Facility Location Problem

CONTENTS

1 INTRODUCTION

Increasingly the global and competitive market requires businesses to operate as members of supply chains in complex networks. Integrating a supply chain helps companies focus on principal business activities and allowing them to respond quickly to changes in customers and improve the flexibility and agility of operations. In recent years, the impact of global competition has forced suppliers, manufacturers and distributors to collaborate efficiently with each other on the entire supply network. Consequently, constant emphasis on productivity gains and customer satisfaction led caused to rapidly evolving business environments characterized by efficient supply chains (JANG et al., 2002; CORDEAU; PASIN; SOLOMON, 2006; BELLAMY; BASOLE, 2013).

This sense, companies are structured as networks (formal and informal), supported by an intense flow of information and materials; providers and customers, or supported by powerful integrated management and sophisticated distribution center systems. The format of this structure results from the following statement: a great opportunity for monetary gains moved from a business-focused management to an approach concerned with controlling the supply chain network (MARTEL; VIEIRA, 2009). In addition, Rice and Hoppe (2001) argued that the new competition would not be company versus company, but supply chain versus supply chain. Companies would compete based on capabilities and advantages obtained from their logistical networks.

Defining the project and managing the supply chain in the competitive business environment is one of managers' most important and difficult problems. (SHEN, 2005). The network design decisions in the supply chain have a significant impact on performance, as they determine the configuration of the supply chain and establish constraints within which other key factors of the network can be used to reduce costs or to increase their responsiveness (CHOPRA; MEINDL, 2011). Thanh, Bostel and Péton (2012) state that the efficient configuration of a logistics network should provide the production and delivery of goods to customers at the lowest cost while satisfying a required service level. A proper Supply Chain

Management (SCM) aims to provide a better level of service, reducing operating costs and contributing to the prosperity of a business (SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2004).

The network design problem is one of the most comprehensive strategic decision problems that need to be optimized for the long-term efficient operation of the entire supply chain (JANG et al., 2002). In this context, Shen (2005) says the that Supply Chain Network Design (SCND) is one of the broader problems related to the supply chain because it involves decisions at the operational, tactical and strategic level. Consequently, supply chain management has emerged as a key area of research among the practitioners of Operations Research over the last decade (FAZLOLLAHTABAR; MAHDAVI; MOHAJERI, 2013).

For this purpose, Operations Research methods and techniques are increasingly used to define the network supply chains in order to provide a solution that is not only feasible but in many cases optimal for this complex problem. Supply chain design and strategic planning problems are often modeled by Mixed Integer Linear Programming - MILP (JAYARAMAN; PIRKUL, 2001; GOETSCHALCKX; VIDAL; DOGAN, 2002; JANG et al., 2002; PARK, 2005; MEIJBOOM; OBEL, 2007). In these models, the location issues are usually represented by integer variable decisions while the product flows along the logistics network are represented by decision variables (THANH, BOSTEL, PÉTON, 2012). Several heuristic methods have been developed to solve the supply chain network problems using different Operations Research techniques and approaches (VIDAL; GOETSCHALCKX, 1997; SHEN, 2007; MELO; NICKEL; SALDANHA-DA-GAMA, 2009).

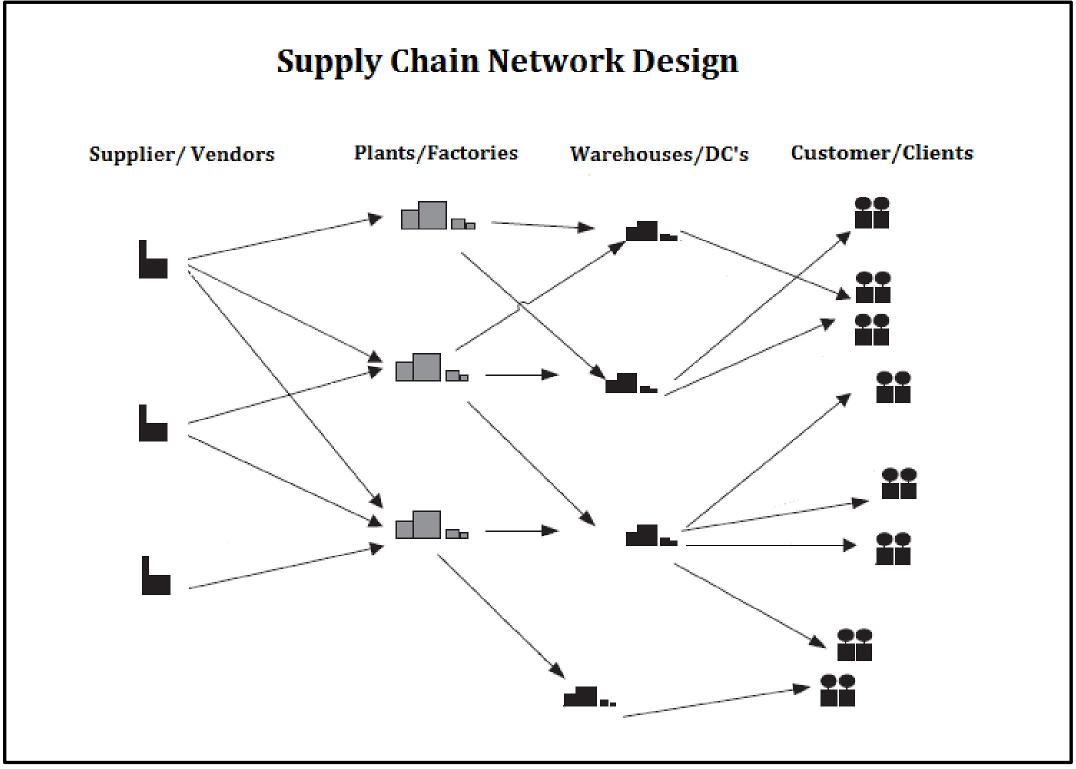
The reason for this study is the importance of successful supply chain management in business operation and the interest of developing and presenting a heuristic method approach to solving complex supply network design involving production and distribution operations. Due to the generality and applicability of the multicommodity paradigm, it has been well studied in many contexts, evidenced, for example, by the vast amount of work on multicommodity flow (RAVI; SINHA, 2004).

Multi-echelon supply chains are commonly used to support manufacturing and industrial organizations. The company may save logistic costs and simultaneously improve service levels by redesigning its supply chain network. Therefore, it is difficult to analyze a large supply chain system in its entirety considering the complex logistical issues involved in this problem (ROMEIJN; SHU; TEO, 2007). Additionally, supply chain network design problems have recently raised a lot of interest since the opportunity of an integrated management of the supply chain can reduce the undesirable events through the network and can affect decisively the profitability of the companies (FAZLOLLAHTABAR; MAHDAVI; MOHAJERI, 2013).

According to these considerations, this work proposes a formulation and mathematical modeling based on Mixed Integer Linear Programming (MILP). The Operations Research methods are implemented using a Linear Programming based on the Rounding procedure and a Local Search techniques. The heuristic approach proposed in this study is essentially a solution method whose computational results show the validation and applicability to solving of a deterministic Supply Chain Network Design problem in a multi-commodity four-echelon system. The Figure 1 illustrates a generic SCND considering four-echelon and single-source requirements.

Moreover, the developed mathematical model allows incorporating usual different kinds of constraints of real world operations, such as a distribution of products from a unique Distribution Center (DC), characterized as a single-source approach. Several researchers studied single source models in this manner (GEOFFRION; GRAVES, 1974; BEASLEY, 1993, KLINCENWICS; LUSS; ROSENBERG, 1986; SRIDHARAN 1993; PIRKUL; JAYARAMAN, 1996; SHEN, 2005).

Figure 1- Supply chain network with four-echelon



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The main contribution of this study is to introduce a heuristic solution approach capable of solving problems for large size instances considering a single-country, single-period context, involving hundreds of products, raw materials, customers, suppliers, factories and distribution centers locations, in reasonable computational time. In the literature review for the most difficult instances, the optimality gap of about 3% for instances with up to 27 suppliers, 22 plants, 12 warehouses, 18 products and 270 customers (THANH; BOSTEL; PETON, 2012). To overcome this difficult, several scenarios and analyzes had been conducted in the computational implementation tests.

In addition, when it is required that each demand zone be provided by single-source, the problem is much more difficult to solve (KLIBI, 2010). In fact, the generalized assignment sub-problem obtained for a given set of facilities is NP-HARD (FISHER; JAIKUMAR; VAN WASSENHOVE, 1986; HOLMBERG; HELLSTRAND,

1998; JAYARAMAN; PIRKUL, 2001; SHEN, 2005; MELO; NICKEL; SALDANHA-DA-GAMA, 2014).

In order to define the purpose of this thesis, in the next section the general and specific objectives that guided this study are described.

1.1 Objectives

The general research objective of this thesis is to propose *a solution method based on a heuristic approach for deterministic supply chain network design to minimize total costs.* The development and application of mathematical modeling consider a multi-commodity four-echelon system.

The specific research objectives are listed as follows:

- Conduct a comprehensive literature research on the mathematical modeling for Supply Chain Network Design considering multiple products in order to support the improvement of the techniques developed in this work;
- Present a mathematical model of Supply Chain Network Design, considering four-echelon operations;
- Develop a heuristics approach to solving problems considering very large instances;
- Computational implementation of the solution method, presenting satisfactory results in relation to the literature;
- Validation of the proposed mathematical modeling by computational experiments and practical application in a realistic production and distribution case.

1.2 Publications

In order to expand this work, preliminary and partial studies has been published in peer-reviewed conferences and journals on Operations Research. We present following a number of papers that were published and presented along this research.

1. FARIAS, E. S.; BORENSTEIN, D. A heuristics approach for supply chain network design in a multi-commodity four-echelon system**. Computers & Industrial Engineering:** Special Issue on Modeling, Algorithms and Metaheuristics for Supply Chain Systems, 2016. (In preparation for submission in Abril).

2. FARIAS, E. S.; BORENSTEIN, D. A multi-start local search heuristic for the supply chain network design problem. In: WORKSHOP ON LOCATION AND NETWORK DESIGN - TRANSPORTATION AND LOGISTIC (LAND – TRANSLOG III), 2016, Santa Cruz, Chile. **Proceedings.** Santiago: Instituto Sistemas Complejos de Ingeniería, 2016.

3. FARIAS, E. S.; BORENSTEIN, D. Modelando o projeto logístico de uma indústria multi-commodity. **Gestão & Produção**, São Carlos, 2016. (approved, awaiting publishing).

4. FARIAS, E. S.; GALVEZ, J. P.; BORENSTEIN, D.; LI, J.Q. A heuristic approach to supply chain network design for a tire industry in brazil. In: BRAZILIAN SYMPOSIUM ON OPERATIONS RESEARCH (XLV SBPO), 45., 2013, Natal. **Proceedings.** Rio de Janeiro: SOBRAPO, 2013.

1.3 Thesis Structure

This thesis is organized as follows. Chapter 2 presents the methodological aspects based on Operations Research applied throughout this study. Chapter 3 reviews the current literature on supply chain network, particularly problems that consider deterministic supply chain network design models. In Chapter 4 the problem formulation and modeling are presented, while Chapter 5 explains the heuristic approach for solving the problem studied. Chapter 6 introduces and analyzes the computational implementations of experiments and results composed by large scale instances. In the Chapter 7, the heuristic approach is applied in a realistic case considering a real world context in a multicommodity industry. Finally, Chapter 8 summarizes our main conclusions and the perspectives for future studies. The references used in this research are presented at the end.

2 METHODOLOGICAL ASPECTS

In order to perform this research, the present work is based on Operations Research and methods. Johnson and Montgomery (1974) define Operations Research as a scientific method of management decision making. In this method, decision problems are transformed into mathematical models which have to determine the optimal decision for the problem examined. To develop the application of problem solving techniques, major phases of a typical operations research study are adopted (WAGNER, 1986; WINSTON, 1994, ARENALES et al., 2007; HILLIER; LIEBERMAN, 2010). These phases can be briefly described as: (i) problem formulation; (ii) mathematical modeling; (iii) computational implementation, (iv) solution and experimental tests and (v) model validation. Below is detailed description of each step of Operations Research conducted in this study.

Step 1: Problem Formulation – this step is very important to determine the appropriate objectives of problem formulation. Thus, a comprehensive review was conducted to understand the main aspects and dimensions involving the supply chain problems. Based on the complexity of network problem studies, we defined a formulation to minimize the total costs of the SCND problem with four echelons for the multi-commodity flow. Our problem formulation considers a single source and single period for a deterministic approach. In the problem formulation proposed, we consider the location and capacity choices for plants and warehouses while suppliers of raw materials are selected. To proceed, we define that the demand of a large number of customer zones must be fully satisfied. Therefore, our well-formulated problem can encompass the main goals of the decision maker or organizations (e.g., maintain stable profits, increase the market share, provide for product diversification, reduce operations cost and optimization of resources).

Step 2: Modeling and Mathematical Formulation - in this step it is necessary to reformulate the problem into a mathematical format and to develop algorithms, heuristics and meta-heuristics to solve the problem at hand. Our mathematical modeling and formulation was based on the previous studies conducted by relevant researchers. In Chapter 4, we detail the formulation and mathematical modeling developed in this study.

The choices of solution strategies are supported by programming languages and computer software packages that enable the construction of the mathematical models. In this respect, we developed the heuristic approach in C++ language. Our heuristic approach considers two main phases: (i) Construction Phase, and (ii) Local Search Phase. In the Construction Phase, we implemented a Linear Programming Rounding to find initial solutions. In the second phase, a Local Search using the Tabu Search meta-heuristic is applied to improve the best solutions obtained in previous phase. The details of the heuristic approach developed in this study are described in Chapter 5.

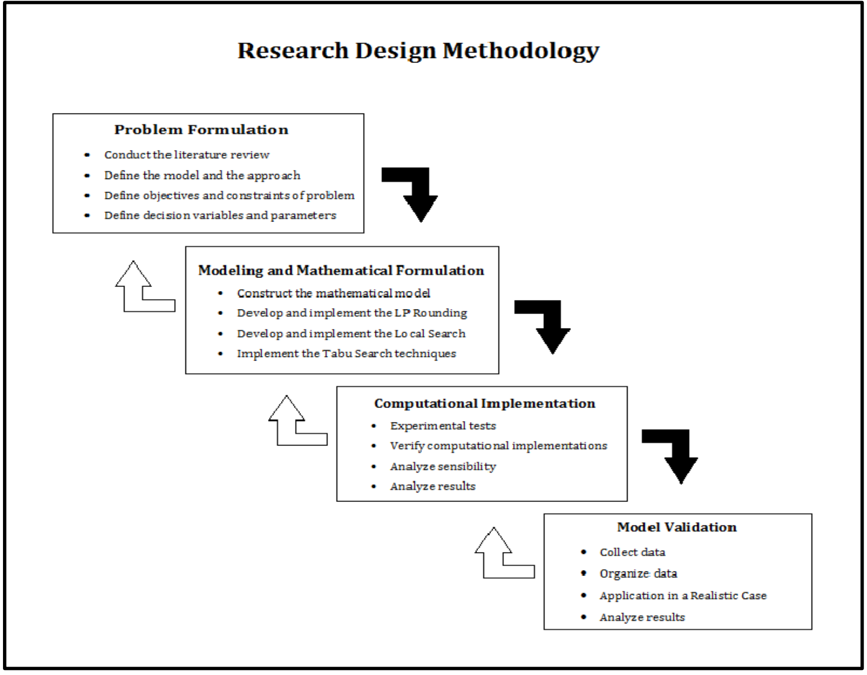
Step 3: Computational Implementation - in order to ensure the correct modeling and computational implementation, the programming developed should represent the mathematical modelling developed and provide the satisfactory result for the problem being studied. Hence, the experimental tests were conducted in 25 large instances. These instances were randomly generated and represent large scale sizes when compared with the literature review.

An important part of this stage was to determine the sensitivity of the solution for model specifications and, in particular, the precision of the input data sets, the appropriateness of the parameters and the quality of results. In this sense, we accomplished extensive experimental tests to verify the accuracy of the model and computational implementations, as well as to define the best parameter setting. Therefore, the testing procedures were applied not only to obtain the problem solutions but also to evaluate whether the model formulated represents the problem studied correctly. The analysis of the results presented solutions within an acceptable optimality range for large scale instances in reasonable computational time. The experimental procedures introduced above are described in detail Chapter 6 called implementing and computational experiments.

Step 4: Model Validation – This step is critical because it is here that the benefits of the research method applied in the study are perceived. In this model validation step, we applied the heuristic approach proposed in the real context of a multicommodity industry. In order to enable the computational implementation, a preliminary data collection was carried out. Demand studies and different market shares were estimated to 270 customer zones for 168 different products. A realistic scenario considering suppliers, plants, DCs, customers and products was structured. In addition, transportation and production costs were defined based on reliable information. The heuristic method was applied in order to obtain an adequate supply chain configuration for the problem faced by the company. The experiments presented satisfactory results in both phases of the proposed heuristic. The construction phase obtained a good solution determining the set of selected DCs for network configuration. In the local search phase, the solution was improved by an efficient Tabu Search technique using the exchange strategy. The Chapter 7 shows in detail the application of heuristics procedure in the realistic case and satisfactory results obtained.

These steps are very important for the success of the work based on Operations Research techniques. Based on the phases previously described, Figure 2 presents a framework depicting the major Operations Research steps developed over this thesis.

Figure 2 - Research design methodology



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The research design methodology illustrated in framework describes the major Operations Research stages developed in this study. In practice, these phases are not developed in isolation; some of these phases are developed simultaneously and influence each other. Therefore, a permanent follow up is necessary to review the preceding stages (e.g. formulation problems, mathematical modelling and computational implementations).

In general, operations research teams focus primarily on constructing and solving mathematical models. However, operations research methods require considerable ingenuity and innovation to develop solutions to complex problems in several fields of research (HILLIER; LIEBERMAN, 2010).

This chapter showed the main phases of the Operational Research method that guided the methodological research of this thesis. The next chapters present the methodological aspects applied to the development of an efficient heuristic based on Operations Research methods.

3 LITERATURE REVIEW

According to Farahani et al. (2014) there is a large volume of literature on Supply Chain Network Design. Hence, the primary goal of literature review was to identify and classify previous studies that examined some aspect of Supply Chain Network Design.

Therefore, this literature review has three parts. The first section presents the overview on general concepts of supply chain and logistics operations, as well as the classification of types of supply chains. In the second section are relevant authors and papers about deterministic Supply Chain Network Design since the mid-1960s. In the last section, we present the main mathematical formulations that inspired the model proposed in this work.

This literature review does not intend to exhaust the topic of research, but rather to present the main contributions by relevant authors involved in Supply Chain Network Design research.

3.1 Overview of the Supply Chain Concept

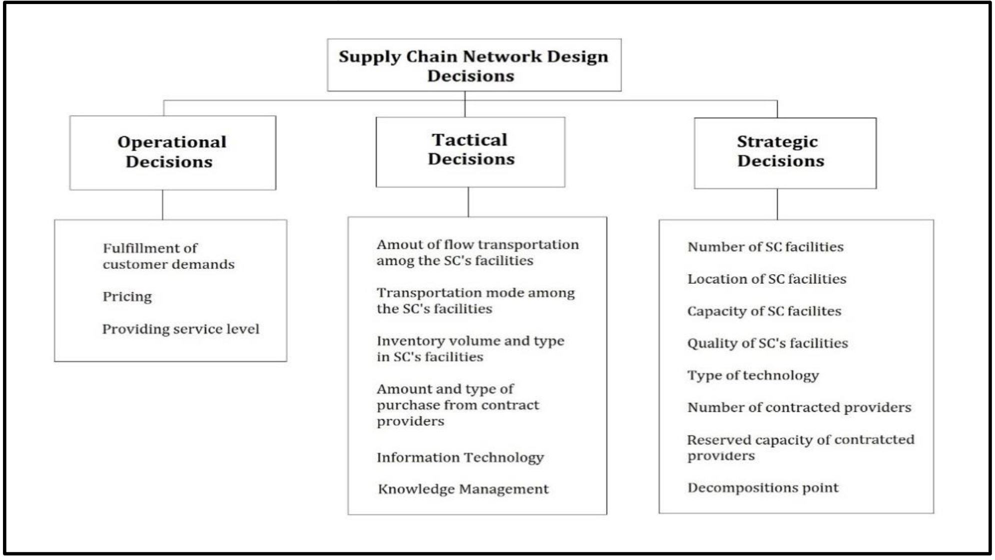
A supply chain can be considered a complex system consisting of a set of activities, workers, technological and physical infrastructures and policies involved in the procurement of raw materials, transformation of these raw materials into products and logistics operations of these products (HASSAN, 2006). A supply chain consists of all the parties involved, directly or indirectly, to fill a client's order, including suppliers, manufacturers, transporters, warehouses and even clients themselves (CHOPRA; MEINDL, 2011).

Yeh (2005) states that the supply chain is often represented as a network, where nodes represent the facilities (suppliers, factories, distribution centers and customers). In this network, arcs connecting these nodes allow the flow of products.

Ballou (2006) explains the logistic concept of grouping together the activities that relate to the flow of products and service for the purpose of managing them collectively. By planning, organization and effective control of corporate activities, logistics aims to provide a better level of service, reducing operating costs and contributing to the prosperity of a business (BOWERSOX; CLOSS; COOPER, 2006).

Successful Supply Chain Management (SCM) requires many decisions regarding the flow of information, products and financial resources. Supply Chain Management is a task that is carried out at three levels: (1) strategic, (2) tactical, and (3) operational. The strategic planning problem is to decide in a broad sense what the overall system configuration should be for production and distribution. Simply put, it is the location of plants and warehouses, selection of suppliers, transportation modes, and designing of the order-processing system (BALLOU, 2006). In this sense, Supply Chain Network Design involves three levels of decisions: strategic, tactical and operational decisions. Common decisions at each level are illustrated in Figure 3. Different decisions are made in the SCND and perhaps the most important one is locating the facilities in different layers of the network (FARAHANI et al., 2014).

Figure 3 - SCND Decision levels



Source: elaborated by author

Faharani et al. (2014) defined different SCM paradigms and their associated concerns and focus area: Lean SC, Agile and Responsive SC, Green SC, Sustainable S and Risk Management SC. One of the main considerations based on these definitions is that all the SCND problems are formulated under the assumption that future markets are monopolies and the competitive environment is ignored.

Supply Chain Network Design problems have raised a lot of interest in many researchers in recent decades. Thus, a vast amount of literature reviews reported problems involving the modeling of the supply chain (VIDAL; GOETSCHALCKX, 1997; OWEN; DASKIN, 1998; ERENGÜÇ; SIMPSON; VAKHARIA, 1999; MELO; NICKEL; SALDANHA-DA-GAMA, 2009; MULA et al, 2010; VISENTINI; BORENSTEIN, 2014).

Important researchers of this theme are concerned about the decision problems in the operational, tactical and strategic levels as shown in Figure 4. The following is a brief sketch of the main contributions of the relevant important literature reviews found.

Vidal and Goetschalckx (1997) conducted a critical review of the strategic models of production and distribution in the global supply chain and identified a higher number of models in order to minimize costs, rather than maximize profits.

In a strategic facility location review, Owen and Daskin (1998) report on literature which explicitly addresses the problems of facility location strategy by considering either stochastic or dynamic problem features. In this paper the authors provide an overview of facility location literature focused on capturing the complex time and characteristics of most real-world problem instances. A wide range of models and solutions are discussed considering mainly the applications of dynamic and stochastic formulations in the uncertainty and complex time problems.

Erengüç, Simpson and Vakharia (1999) present an invited review showing a taxonomic framework for analyzing supply chains from an operational perspective and identify relevant decisions at each stage of the supply chains network. From an operational perspective, the supply chain network is divided into three stages: the first of stage the supply network consists of all suppliers who provide any raw materials to those that precede the plants; in the second stage of the supply chain the direct inputs from the suppliers are transformed into the products or services; the final stage focuses on the distribution network to satisfy the final demand of goods or services. In addition, reviews and critiques evaluate the relevant literature on production and planning in supply chains.

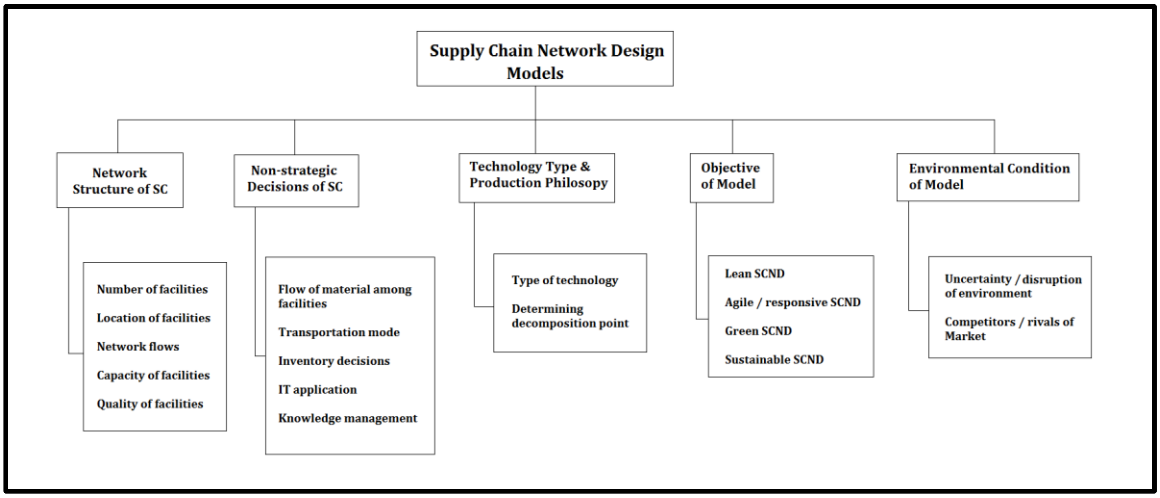
Melo, Nickel and Saldanha-da-Gama (2009) provide a review of the literature about the different extensions of location models in the context of Supply Chain Management (SCM). This review identified the characteristics required by a facility location model to adequately address SCM planning needs. The authors point out that the literature still requires intensive research. Studies considering the stochasticity modeling in SCM still need to be incentivized. Indeed, a few papers addressing stochastic parameters combined with other aspects were found. The literature integrating uncertainty in SCM considering location decisions is still scarce. Further, the authors state that a few papers introduce relevant tactical and operational decisions in SCM such as procurement, options routing and transportation modes. In addition, they noted that the large majority of location models within SCM are mostly cost-oriented. One of these models focused on maximizing the potential return on facility investment, contradicting the fact that SCND decisions are usually evaluated on return rate. From this review regarding the methodology that has been developed to solve SCND problems, the authors observed a rich and varied group of solution techniques and found a growing stream of research aiming at the integration of strategic, tactical and operational decisions in supply chain planning.

Mula et al. (2010) presents a review of mathematical programming models for production and transport planning considering eight aspects: supply chain structure, decision level, supply chain modeling approach, purpose, shared information, model limitations, the novelty contributed and practical application. In this extensive and comprehensive review, the authors intend to show that the most widely used modeling approach is mixed integer linear programming and that most models aim at the minimization of the total supply chain costs. Additionally, the majority of models are validated by numerical examples than applied case studies to real supply chain network.

In a recent review, Visentini and Borenstein (2014) present and discuss features of mathematical models for Global Supply Chain Network Design. The research selected 111 papers published between 2000 and 2013 in the main Operational Research journals. The 22 papers analyzed in depth identified emerging issues and opportunities for the development of new mathematical models and solution techniques. After extensive categorization and analysis, the authors list some aspects that can be improved for future research involving SCND. One of these is the integration of decisions of the global supply chain at the strategic and operational levels. This integration considers that internal and external decisions should take into account major evaluations such as: minimal amounts of suppliers, budget constraints, geographic location of suppliers, for example. The authors suggest that research in SCND should consider stochastic variables and multi-period models for a more reliable representation of reality activities involved in global logistics operations. Additionally, the inclusion of transfer fees should be considered in the modeling of a global supply chain, ignoring these rates may affect the company's profitability and the economic viability of the project. Finally, although it increases the complexity of the problem, the study practical cases is presented as a relevant opportunity for new SCND models because it exhibits the models developed in real applications.

Farahani et al. (2014) present an overview of classification, models, solution techniques and applications in SCND. The authors argue that some specific assumptions are usually imposed by the environmental conditions and each makes special decisions about the supply chain network structure. A framework showing the summary of strategic questions is illustrated in Figure 4. In this paper, they state that the goal of SCND is to design an efficient network structure for new chains or to reengineer an existing network to increase its total value. An efficient SCND requires decisions about the number of chain layers, location and facility capacity in each layer and making decisions about the flow of raw materials and products throughout the network. It should be considered that the condition of the market and business usually determines the inclusion of some variables design the models.

Figure 4 - Comprehensive specifications of SCND problems



Fonte: Adapted from Farahani et al, 2014.

In this section, we were introduced to the main concepts involving the terms supply chain and logistics. Similarly, concepts and major literature reviews wr presented addressing the modeling of the Supply Chain Network Design. The following section will present the main researchers and works that specifically addressed deterministic supply chain network models.

3.2 Deterministic Supply Chain Network Design Models

Since the mid-1960s, discrete location has evolved into a mature field of research. The vast majority of the literature is dedicated to single-period problems with a static customer demand pattern (MELO; NICKEL; SALDANHA-DA-GAMA, 2009).

Due to the importance of efficient design of supply chain networks, facility location problems in the context of Supply Chain Management (SCM) have always attracted the attentions of many researchers. Facility location models and, in particular discrete facility location models, can be considered as the foundation of Supply Chain Network Design models (KLIBI, 2010).

Facility Location Problems (FLP) consider a single product and a single production and distribution echelon with Uncapacitated (UFLP) or Capacitated

(CFLP) facilities (KLIBI et al. 2010). The Uncapacitated Facility Location Problem (UFLP) involves locating an undetermined number of facilities to minimize the sum of the fixed costs and the variable costs of serving the market demand from these facilities. In some cases, it is more realistic to incorporate the capacity limitations on the facilities to be established (VERTER, 2011). In the CFLP problem, demand can be supplied from more than one source. However, if it necessary for each demand zone to be supplied from a single source, it is called CFLPSS (Capacitated Facility Location Problem Single Source), which in turn is much more difficult to solve. An immediate generalization of UFLP is the Multiproduct Uncapacitated Facility Location Problem (MUFLP) that relaxes the single product assumption.

Warszawski (1973) and Warszawski and Peer (1973) were among the first to study the multicommodity location problem. Neebe and Khumawala (1981) presented an improved algorithm for multicommodity location problems. These models assume fixed location costs and linear transportation costs, and consider that each warehouse can be assigned at most one commodity (SHEN, 2005). Klincewicz, Luss and Rosenberg (1986) were the first researchers that studied a Multiproduct Uncapacitated Facility Location model without any restrictions on the number of products at each facility. One of the earliest multi-echelon formulations is by Kaufman, Eede and Hansen (1977), which determined the locations of a set of facilities and a set of warehouses simultaneously. But this paper ignored the cost implications of possible interactions among the facilities at different echelons.

In order for enterprises to meet their strategic goals, a set of structural and infrastructural decisions must be made, which typically involve long-term commitments with regards to the planning and operation of the supply chain. These structural decisions, facility design decisions include location, capacity, product sets, and production and operation technologies at various facilities. The usual objective of this problem, in this sense, is to minimize costs or maximize profits. Mathematical models of this kind are generally called “Production-Distribution System Design Problems - (PDSDP)” (DASCI; VERTER, 2009).

A pioneering effort in the use of a simulation model for location decisions by Schycon and Maffei (1960) describes a consulting assignment at the Heinz Company. The approach used in this research has since been applied to many firms with multiple factories and multiple warehouse operations. In this historical physical distribution simulation the original model was essentially "static" and the network distribution configuration comprised: 9 plants, 3 regional distribution centers and 43 warehouses, incorporating 50 different product patterns for customers. Model validation was carried out by replication in other firms with distribution cost operations. The model studied in detail 10 alternative distribution configurations in addition to the present one. The final recommendations were to leave unchanged the 9 factories and 3 regional DC's, while reducing the 43 warehouses to 32, some of which were at new locations.

Kuehn and Hamburguer (1963) propose a Mixed Integer Linear Program (MILP) and a heuristic solution is produced. This work outlines a heuristic computer program for locating warehouses providing considerable flexibility in modeling the problem to be solved and can be used to study large-scale problems. They propose 12 problem instances involving combinations of three sets of factory locations and four levels of warehouse costs. The sample problems considering a single commodity and the transportation costs are assumed to be proportional to the distances. The set of customer zones comprises 50 large cities in the United States, and 24 of these are also identified as alternative warehouse locations. The computational experiments were carried out with 5 facilities (VERTER, 2011).

According to Verter (2011), the most influential paper following the CFLP formulation designed in Kuehn and Hamburger (1963) was the contribution by Geoffrion and Graves (1974). Geoffrion and Graves (1974) conducted a seminal paper that deals with the distribution system design incorporating multi-commodity. This work is characterized by approaching multiple products, capacity of the factories and distribution centers, product flow and a single-sourcing policy that requires serving each customer from a single distribution center. In this study they used the Bender decompositions method for a solution considering the linear programming sub-problem and decomposing these sub-problems into several independent transport problems. Given the existing plant and customer location, a

Bender Decomposition approach had to be established to determine the optimal number and location of DCs. The model was applied to a food industry that produced about a hundred products at 14 locations, with national-wide distribution through a dozen distribution centers.

Cohen and Lee (1989) presented a deterministic Mixed Integer Problem (MIP) model to maximize the global after-tax profits considering optimal policies for facility network design and material flows. The decision variables for the network design issues included location and the capacities of all production facilities considering sourcing decisions, production, and distribution planning. The model finds the optimal resource deployment for a particular policy option.

Pirkul and Jayaraman (1996) developed an MIP model for a multi-product, tri-echelon, capacitated plant and warehouse location problem. The model objective was to minimize the sum of fixed costs of operating the plants and warehouses as well as the variable costs of transporting multiple products from the factories to the warehouses and finally to the customers. The authors employed Lagrangian relaxation for the model and also presented a heuristic procedure with feasible solutions for the problem. A set of large-scale instances using real data was solved and results in randomly generated instances with up to 10 plant and 20 warehouse locations, 100 customer zones and 3 products. They also present results on real-life instances with 5 plant and 30 warehouse locations, 75 customer zones and 10 products.

Jayaraman and Pirkul (2001) incorporated supplier selection into a multi-commodity problem setting. The computational results indicate that a proposed Lagrangian relaxation based procedure with the heuristic procedure presented good and effective results within an acceptable time. In the computational experiments the authors solved a wide range of problems for a number of 150 customer zones, 30 warehouses, 10 plants, 5 products, 3 suppliers and 2 raw materials in the largest instance.

Considering a multicommodity supply chain design problem, Shen (2005) proposed a formulation as a nonlinear integer program using a Lagrangian-relaxation solution algorithm. This was the first multicommodity integrated supply chain design model that includes economies of scale supply chain cost terms in the objective function (SHEN, 2005). The results presented in this approach are very good compared with an algorithm proposed in Verter and Daskin (2001).

Altiparmak et al. (2006) developed mixed-integer non-linear programming for multi-objective optimization of a Supply Chain Network and a Genetic Algorithm (GA) approach to solve a problem in a plastic products industry in Turkey. The authors considered three objectives: minimization of total costs comprised of fixed costs of plants and distribution center, maximization of customers services in terms of acceptable delivery time and maximization of capacity utilization balance for distribution centers. This work involved a four-echelon stages model considering suppliers, plants, distribution centers and customers and single-product.

Lee and Dong (2008) introduce a Tabu Search (TS) approach for the design of a two-echelon network. The proposed model includes some practical elements of SCND such as the direct shipment of a single commodity from plants to customers and location decisions concerning both plants and warehouses. Computational experiments demonstrate high-quality solutions for end-of-lease computer products with a modest computational overhead.

Lee and Kwon (2010) proposed a Mixed Integer Programming (MIP) model for distribution center operation planning with three multi-stages. The authors presented a hybrid heuristic for a distribution center using tabu search and decomposed optimization. The heuristic are constructed using the decomposition of the networks to gain in the computational efficiency, and tabu search to use the neighbor solutions. The tabu search applied used a priority rule designed by using the so-called Unit Cost Ratio. The performance of the heuristic algorithm is applied using several instances generated for evaluation with respect to the number of plants, distribution centers, customers and products. The results of performance in large size instances considering 10 plants, 20 warehouses, 80 customer and 5 products present a GAP of 3.95% in average from the best solution.

Thanh, Bostel and Péton (2010) propose a heuristic approach based on the linear relaxation of the MILP for a logistic network design and planning considering multi-period, multi-echelon and multi-commodity. The numerical results show good solutions for medium-size instances with the average optimality gap after 3 hours of computation being 1.5%. However, for the largest instances, the resulting MILP presents the average optimality gap of 3.67% and even 6% for some large instances, after 3 hours of computation. Following up this work, Thanh, Bostel and Péton (2012) incorporated a difference of convex functions programming in this same LP-rounding method. The degradation of objective function is generally less than 1%. However, for the most difficult instances, the optimality gap of about 3% for instances with up to 12 warehouses, 18 products and 270 customers.

In this section, we present concepts and a brief history of scientific production in Supply Chain Network Design, especially for deterministic approaches, considering the most relevant papers consulted in this research. The next section presents the mathematical formulations that inspired the mathematical modeling proposed in this thesis.

3.3 Modeling Supply Chain Network Design

This section presents three important mathematical formulations developed for SCND involving the problem of location, multi-commodity distribution and production flow. These works were developed at different times since the 1970s and inspired and supported several other works in this field research.

Geoffrion and Graves (1974) were among the first to solve the version of the multi-commodity location problem. In this model, production capacity at each plant for each product is known and fixed. The product demands for multiple customer zones are known and fixed. The demands are satisfied by shipping products through distribution centers (DC) with each customer zone assigned exclusively to a single DC. The potential site locations are selected to minimize total network costs. The costs consist of fixed costs to use a DC, a variable operating cost (based on the amount of products shipped through a DC), and total transportation cost involving the transport of products from a plant to a DC and a customer zone. This model formulation is as follows.

Min Z =

$$\sum_{p,j,k,l} c_{pjkl}\, x_{pjkl} + \sum_{k} \left[f_k z_k + v_k \sum_{p,l} d_{pl} y_{kl} \right] \qquad (1a)$$

Subject to

$$\sum_{p,j,k,l} x_{pjkl} \leq s_{pj} \qquad \forall\, p, j \qquad (1b)$$

$$\sum_{j} x_{pjkl} = d_{pl} y_{kl} \qquad \forall\, p, k, l \qquad (1c)$$

$$\sum_{k} y_{kl} = 1 \qquad \forall\, l \qquad (1d)$$

$$\underline{V_k} z_k \leq d_{pl} y_{kl} \leq \overline{V_k} z_k \qquad \forall\, k \qquad (1e)$$

$$z_k \in \{0,1\} \qquad \forall\, k \qquad (1f)$$

$$y_{kl} \in \{0,1\} \qquad \forall\, k, l \qquad (1g)$$

$$x_{ijkl} \geq 0 \qquad \forall\, i, j, k, l \; (1h)$$

In this model p, j, k and l are the indices for products, distribution centers (DC) and customer zones, respectively. The objective function (1a) specifies the transportation costs of each product to each customer zone and the total distribution center operating costs which are f_k the fixed cost. In this formulation, variable c_{pjkl} is the linear transportation cost and variable x_{pjkl} is the amount shipped. The integer decision variable z_k is 1 if a DC is acquired at site k and y_{kl} is

1 if product *P* demands are supplied to customer zone *l* through DC *k*. The unit cost of throughput for a DC is represented by $v_k$variable.

Constraints (1b) imposes the capacity for each plant. The constraints (1c) satisfied demands for a customer zone. Constraints (1d) ensures that each customer zone is supplied by a single DC.

The Constraints (1e) representing the total throughput for a DC is constrained between a given lower $\underline{V_k}$ and upper bound $\overline{V_k}$ and also enforces the correct logical relationship between z_k and y_{kl} decision variables if customer zone *l* can only be supply by a DC site *k* provided a DC is located at that site. Constraints (1f) and (1g) define the integer decision variables and Constraints (1h) is the non-negativity restriction.

The model is computationally complex and authors are able to develop an efficient solution procedure based on Bender's decomposition. They solved their problem by considering the linear programming sub-problem and decomposing it into as many different independent transportation problems as there are commodities. The formulation and modeling was applied to a real problem of a food industry with a hundred products produced at 14 locations with a national geographic distribution.

Daskin (1995) discusses the problem of multiple products in the flow distribution system presenting a general case involving the transport of products from the factory to the consumer market directly or through distribution centers. The mathematical formulation for this problem is defined as follows:

Parameters:

h_i^k= demand for product *k* in market *i*;

f_j = fixed cost location of the distribution center at site *j*;

c_{ijm}^k = cost of production per unit of product *k* in factory *m* transported to the market *i* by the distribution center at site *j;*

S_m^k = plant capacity m to produce the product k. In this situation, it is assumed that every factory production capacity for different products is independent. In general, this does not occur in real problems.

M = a very large number.

Decision variables:

Y_{ijm}^k = product flow k in factory m to the market i through the distribution center j;

X_j = 1 if a distribution center is located at site j, 0 otherwise.

Mathematical Model Formulation:

$$\min \sum_j f_j X_j + \sum_i \sum_j \sum_m \sum_k c_{ijm}^k Y_{ijm}^k \qquad (2a)$$

Subject to

$$\sum_i \sum_m \sum_k Y_{ijm}^k \leq MX_j \qquad \forall\, j \qquad (2b)$$

$$\sum_j \sum_m Y_{ijm}^k \geq h_j^k \qquad \forall\, i, k \qquad (2c)$$

$$\sum_i \sum_j Y_{ijm}^k \leq S_m^k \qquad \forall\, m, k \qquad (2d)$$

$$Y_{ijm}^k \geq 0 \qquad \forall\, i, j, m, k \qquad (2e)$$

$$X_j = \{0, 1\} \qquad \forall\, j \qquad (2f)$$

The objective function (2a) minimizes the sum of the fixed costs for location of distribution centers and variable costs. Note that a large number of costs can be incorporated into the variable cost (c_{ijm}^k) including the unit cost of production in factory m, unit cost of transport between factory m and the distribution center located in j, any unit variable cost in distribution center in j, and the cost of transport between location *j* and market *i*. All these depend on unit costs of the product concerned.

Constraints (2b) ensures that the flow of product through the distribution center can only be positive if the distribution center location *j*. Constraints (2c) guarantees that the total amount of product *k* shipped to market *i* by all plants and distribution centers must be greater than or equal to the demand of product *k* in the market *i*. Similarly, the Constraints (2d) ensures that the total amount of product *k* does not exceed the production capacity of plant *m*. Finally, Constraints (1e) and (1f) are non-negativity and integer restrictions, respectively.

The general model presented by Daskin (1995) does not discuss the capacity of distribution centers and does not use restriction to ensure that a market is supplied by only one distribution center, in other words, it is not a single-source model approach.

In the mathematical modeling of Jayaraman and Pirkul (2001) three major cost structures are proposed: production costs that incorporate fixed and variable costs of the plants (factories), fixed and variable costs for the transportation of raw materials from suppliers to plants, and fixed and variable distribution costs of finished products from factories to customers zones through distribution centers.

The mathematical modeling is presented below.

I = set of customer zones;

J = set of warehouses;

K = set of manufacturing plants;

L = set of product groups;

R = set of raw materials;

V = set of vendors;

o_j = annual fixed cost for operating a warehouse j;

g_k = annual fixed cost for operating a plant k;

v_j = unit cost of throughput for a warehouse at site j;

v_{lk} = unit production cost for product l at plant k;

t_{vkr} = unit transportation and purchasing cost for raw material r from vendor v to plant k;

c_{ijkl} = unit transportation cost for product l from plant k via warehouse j to customer zone i;

a_{il} = demand for product l at customer zone i;

W_j = annual throughput at warehouse j;

D_k = capacity of plant k;

SUP_{vr} = supply capacity of vendor v for raw material r;

u_{rl} = utilization rate of raw material r per unit of finished product l;

s_l = capacity utilization rate per unit of product l;

W = maximum number of warehouses;

P = maximum number of plants.

The following decision variables are used in the model:

z_j = 1 if warehouse j is open, 0 otherwise;

p_k = 1 if plant k is open, 0 otherwise;

y_{ij} = if warehouse j serves customer zone i, 0 otherwise;

b_{vkr} = quantity of raw material r shipped from vendor v to plant k;

x_{lk} = quantity of product l produced at plant k;

q_{ijkl} = quantity of product l shipped from plant k via warehouse j to customer zone i.

Problem P

$$\min \sum_j o_j + \sum_i \sum_j \sum_l v_j\, a_{il} y_{ij} + \sum_k g_k\, p_k + \sum_l \sum_k v_{lk}\, x_{lk} + \sum_v \sum_k \sum_r t_{vkr}\, b_{vkr} + \sum_i \sum_j \sum_k \sum_l c_{ijkl}\, q_{ijkl} \tag{3a}$$

Subject to

$$\sum_{j} y_{ij} = 1 \qquad \forall\, i \qquad (3b)$$

$$\sum_{i}\sum_{j} a_{il} y_{ij} \leq W_j z_j \qquad \forall\, j \qquad (3c)$$

$$\sum_{j} z_j \leq W \qquad (3d)$$

$$\sum_{k} q_{ijkl} = a_{il}\ y_{ij} \qquad \forall\, i,j,l \qquad (3e)$$

$$\sum_{k} b_{vkr} \leq \mathrm{SUP}_{vr} \qquad \forall\, v,r \qquad (3f)$$

$$\sum_{l} u_{rl} x_{lk} \leq \sum_{k} b_{vkr} \qquad \forall\ r,k \qquad (3g)$$

$$\sum_{l} s_l x_{lk} \leq \sum_{k} D_k\, p_k \qquad \forall\ k \qquad (3h)$$

$$\sum_{i}\sum_{j} q_{ijkl} \leq x_{lk} \qquad \forall\ l,k \qquad (3i)$$

$$\sum_{k} p_k \leq P \qquad (3j)$$

$$z_j = \{0,1\} \qquad \forall\, j \qquad (3k)$$

$$p_k = \{0,1\} \qquad \forall\ k \qquad (3l)$$

$$y_{ij} = \{0,1\} \qquad \forall\ i,j \qquad (3m)$$

$$b_{vkr} \geq 0 \qquad \forall\ v,k,r \qquad (3n)$$

$$x_{lk} \geq 0 \qquad \forall\ k,l \qquad (3o)$$

$$q_{ijkl} \geq 0 \qquad \forall\ i,j,k,l \qquad (3p)$$

The objective function minimizes the total cost of the supply chain network. This includes the fixed cost of operating and opening plants and warehouses, the variable cost of production and distribution, costs of transportation of raw material from vendors to plants to customer outlets through warehouses.

Constraints (3b) represents the unique assignment of a warehouse to a customer. Constraints (3c) imposes the warehouse annual throughput. Constraints (3d) limits the number of warehouses that can be open. The customer demand for all products is satisfied by the Constraints (3e). Constraints (3f) describes the raw material supply restriction. Raw material requirements for production are represented by Constraints (3g). The plant production capacity constraint is described by Constraints (3h). In Constraints (3i), the total quantity of product shipped from a manufacturing plan to customer outlets through warehouses cannot exceed the amount of that product that we produce in that plant. Finally, Constraints (3j) limits the number of plants that are opened. Constraints (3k), (3l) and (3m) impose the integrality restriction on the decision variables z_j , p_k e y_{ij} and constraints (3n), (3o) and (3p) impose the non-negativity restriction on the decision variables b_{vkr}, x_{lk} e q_{ijkl} .

The Lagrangian relaxation scheme is applied to the model. To solve the dual problem arising in this approach a subgradient optimization method is used. These relaxations produced lower bounds on the optimal objective function value for the problem. In order to find feasible solutions, and an upper bound, a heuristic procedure was applied. Jayaraman and Pirkul (2001) present numerical results to compare the performance of the heuristic procedure to the quality of solutions that are obtained from the lower bounds.

Additionally, the model and solution procedure developed were applied to real world data obtained from a health-care product manufacturer in the US. In terms of transportation and distribution costs, this application consisted in two raw materials from two major suppliers, 10 major products in 5 manufacturing plants. The demand consisted of 75 customer zone with 30 possible warehouse locations. They applied real world data to input in the model structure. The results were interesting, as the load ratios of the open warehouse and plants kept increasing, the solution time and the gaps also increased within acceptable limits (JAYARAMAN; PIRKUL, 2001). The results present a gap between the feasible solution and the Lagrangean bound ranged between 1.36% and 2.65% within times ranging between 45 and 88 seconds. The authors say that the heuristic was able to find solutions that would have been practically unobtainable with commercial integer programming codes. Further, the enterprise took advantage of economies that could be achieved by such flow of products to a customer zone.

The modeling and implementations developed by Geoffrion and Graves (1974) and Jayaraman and Pirkul (2001) are limited by number of entities and facilities involved in the supply chain network problems. Logistical projects include a dozen of warehouse candidates and hundreds of customer zones and products. Establishing groups of commodities or small numbers of entities reduces the complexity of the supply chain network problems and imposes limits on the application of these models.

Although Jayaraman and Pirkul (2001) address a four-echelon supply chain network, the largest instances solved in this paper consider problems with 150 customer zones, 30 warehouses, 10 plants and only 5 products. The experimental results show a GAPs average of 2.70% and higher GAPs over 3.50%.

In this way, the heuristic approach proposed in this thesis intends to overcome these limitations solving problems considering a large number of commodities with reasonable GAPs in computational results.

4 MODELING AND MATHEMATICAL FORMULATION

In this chapter the model developed represents a cost minimization problem subject to constraints associated with locating and operating the multi-commodity industry production and distribution facilities, considering four-echelon operations among vendors, plants, warehouses and customer zones. A Mixed Integer Linear Programming (MILP) formulation by Jayaraman and Pirkul (2001) for Supply Chain Network Design (SCND) is reconsidered. The main objective in this formulation is to minimize the total fixed and variable cost associated with a flow of raw materials and products in the supply chain network. The constraints are imposed on the raw materials supply, production capacity, warehouse capacity and demand of customer zones.

The model presents three major cost structures: fixed and variables costs of distributing goods from the plants to the customer zones through open warehouses; cost of transporting raw materials from vendors to plants; and production cost which takes into account consider both the fixed cost of operating the factories and variable cost associated with production.

The modeling presents a multi-commodity single-period Supply Chain Network Design (SCND) modeling and formulation, considering two types of variables. The strategic ones are binary variables and refer to the location of facilities and the single-source strategy. The tactical ones are continuous variables and refer to raw material and product flows in the arcs of the network, as follows: (i) the quantity of materials from vendors to plants and (ii) the products shipped from plants to distribution centers (DCs). There are three types of integer variables: for opening plants, for opening warehouses and for serving a customer zone from a warehouse.

We assume the following notation to define the mathematical modeling:

Index Sets: introduces the index sets to be used

Symbol	Description
$\boldsymbol{C}$	Set of customer zones, indexed by *c*
$\boldsymbol{W}$	Set of warehouses, indexed by *w*
$\boldsymbol{F}$	Set of factories (plants), indexed by *f*
$\boldsymbol{R}$	Set of raw materials, indexed by *r*
$\boldsymbol{V}$	Set of vendors (suppliers), indexed by *v*
$\boldsymbol{S}$	Set of products, indexed by *s*

Parameters: summarizes parameters and costs

Symbol	Description
$\boldsymbol{d_{cs}}$	demand for product $s \in S$ at customer zone $c \in C$
$\boldsymbol{U_f}$	maximum number of factories (plants) that are opened $f \in F$
$\boldsymbol{U_w}$	maximum number of warehouses (distribution centers) that are opened $w \in W$
$\boldsymbol{u_{rs}}$	the utilization rate of raw material $r \in R$ per unit of finished product $s \in S$
$\boldsymbol{u_s}$	capacity utilization rate per unit of $s \in S$
$\boldsymbol{CAP_w}$	annual throughput at warehouse $w \in W$
$\boldsymbol{CAP_{vr}}$	supply capacity of raw material $r \in R$ from vendor $v \in V$
$\boldsymbol{CAP_f}$	capacity of factory $f \in F$
$\boldsymbol{CT_f^o}$	annual fixed cost of operating factory $f \in F$
$\boldsymbol{CT_w^o}$	annual fixed cost of operating warehouse $w \in W$
$\boldsymbol{CT_w^g}$	unit cost of throughput at warehouse $w \in W$
$\boldsymbol{CT_{fs}^p}$	unit production cost of product $s \in S$ at factory $f \in F$
$\boldsymbol{CT_{fvr}^t}$	unit transportation cost of raw material $r \in R$ from vendor $v \in V$ at factory $f \in F$
$\boldsymbol{CT_{fws}^t}$	unit transportation cost of product $s \in S$ from factory $f \in F$ to warehouse $w \in W$

$\boldsymbol{CT^t_{wcs}}$	unit transportation cost of product $s \in S$ from warehouse $w \in W$ to customer zone $c \in C$
$\boldsymbol{o_w}$	penalty cost for each unit of throughput violation of warehouse $w \in W$

Decision variables: describes the decision variables

Symbol	**Description**
$\boldsymbol{a_w}$	binary variable, and it is 1 if warehouse $w \in W$ is selected, and 0 otherwise
$\boldsymbol{b_f}$	binary variable, and it is 1 if factory $f \in F$ is selected, and 0 otherwise
$\boldsymbol{g_{wc}}$	binary variable, and it is 1 if customer $c \in C$ is assigned to warehouse $w \in W$, and 0 otherwise
$\boldsymbol{z^s_{fw}}$	amount of product $s \in S$ shipped from factory $f \in F$ to warehouse $w \in W$
$\boldsymbol{y^r_{vf}}$	amount of raw materials $r \in R$ shipped from vendor $v \in V$ to factory $f \in F$

The single-source SCND problem is formulated by the following Mixed Integer Linear Programming.

Function Objective

$$\begin{aligned}
\min \sum_{w\in W} CT^o_w\, a_w + \sum_{f\in F} CT^o_f\, b_f + \sum_{w\in W}\sum_{c\in C}\sum_{s\in S} CT^g_w\, d_{cs} g_{wc} + \sum_{f\in F}\sum_{w\in W}\sum_{s\in S} CT^p_{fs}\, z^s_{fw} \\
+ \sum_{f\in F}\sum_{r\in R}\sum_{v\in V} CT^t_{fvr}\, y^r_{vf} + \sum_{f\in F}\sum_{w\in W}\sum_{s\in S} CT^t_{fws}\, z^s_{fw} \\
+ \sum_{w\in W}\sum_{c\in C}\sum_{s\in S} CT^t_{wcs}\, d_{cs} g_{wc} \\
+ \sum_{w\in W} P_w\, o_w \qquad (4a)
\end{aligned}$$

Subject to

$$\sum_{w \in W} g_{wc} = 1 \qquad \forall\, c \in C \qquad (4b)$$

$$\sum_{c \in C} \sum_{s \in S} d_{cs} g_{wc} \leq CAP_w\, a_w + o_w \qquad \forall\, w \in W \qquad 4(c)$$

$$\sum_{c \in C} d_{cs} g_{wc} \leq \sum_{f \in F} z_{fw}^{s} \qquad \forall\, s \in S, \forall\, w \in W \qquad (4d)$$

$$\sum_{f \in F} y_{vfr} \leq CAP_{vr} \qquad \forall\, r \in R, \forall\, v \in V \qquad (4e)$$

$$\sum_{w \in W} \sum_{s \in S} u_{rs} z_{fw}^{s} \leq \sum_{v \in V} y_{vf}^{r} \qquad \forall\, r \in R, \forall\, f \in F \qquad (4f)$$

$$\sum_{w \in W} \sum_{s \in S} u_s\, z_{fw}^{s} \leq CAP_f b_f \qquad \forall\, f \in F \qquad (4g)$$

$$\sum_{w \in W} a_w \leq U_w \qquad (4h)$$

$$\sum_{f \in F} b_f \leq U_f \qquad (4i)$$

$$a_w = \{0,1\} \qquad \forall\, w \in W \qquad (4j)$$

$$b_f = \{0,1\} \qquad \forall\, f \in F \qquad (4k)$$

$$g_{wc} = \{0,1\} \qquad \forall\, w \in W, \forall\, c \in C \qquad (4l)$$

$$z_{fw}^{s}, y_{vf}^{r}, o_w \geq 0 \qquad \forall\, r \in R, v \in V, f \in F, s \in S, w \in W \qquad (4m)$$

The objective (4a) is to minimize the sum of the annual cost of warehouses, the throughput costs of warehouses, the production cost of factories, the transportation costs of raw material to factories and transportation costs of products from factories to customers through the warehouses.

Constraints (4b) ensure that each customer zone is assigned to one warehouse. Constraints (4c) guarantees that the capacity of each warehouse is not violated. Constraints (4d) force each warehouse to have sufficient products for its associated customers. Constraints (4e) ensures that the capacity of any raw material at any vendor is satisfied. Constraints (4f) give the relation between raw materials and products. Constraints (4g) guarantee that the capacity of any factory is respected. Constraints (4h) and (4i) impose an upper bound of warehouse and factories, respectively. Constraints (4j), (4k) e (4l) are the integrality restrictions, and (4m) represented the no-negativity constraints.

The next chapter describes the heuristic solution method developed to solve this problem.

5 HEURISTIC APPROACH

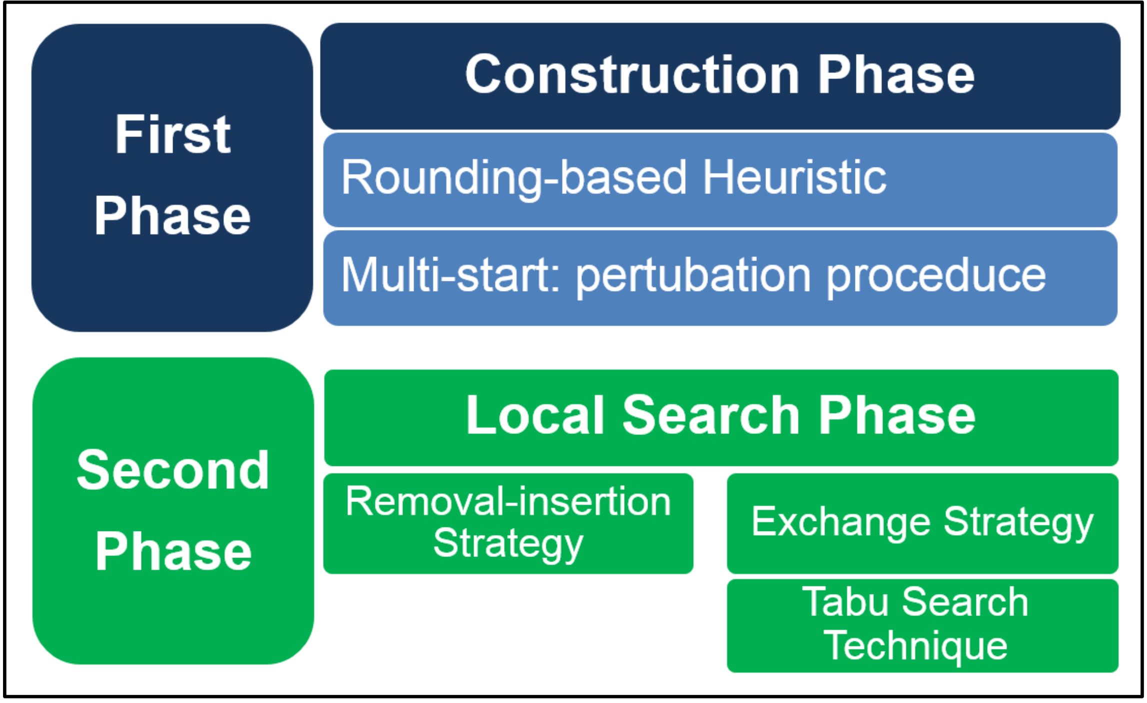
In order to overcome the computational difficulties associated with production an acceptable solution, our heuristic approach combines a Linear Programming Rounding based strategy with Local Search methods.

The developed heuristic approach consists of two intertwined phases, as follows:

1) **Construction Phase:** in the first phase, a linear programming based rounding heuristic is developed to find initial values for the integer variables (warehouse locations and assigning of customers to warehouses). Simultaneously a multi-start procedure is applied to explore different solution spaces and consequently generate different solutions from the last iteration.
2) **Local Search Phase:** the second phase of the heuristic uses local search methods to improve the best initial solution delivered by the construction phase. In this phase, two different strategies are implemented: removal-insertion and exchange strategies. After implementation of both, the exchange strategy showed better results when compared to the insert-removal strategy. Thus, we opted for the implementation of the tabu search technique with exchange strategy to improve the performance of local search.

The details and steps of the heuristic approach developed in this study are described in the following section as shown in the framework illustrated in Figure 5.

Figure 5 - Heuristic approach for SCND



Fonte: Prepared by the author

5.1 Construction Phase

5.1.1 LINEAR PROGRAMMING ROUNDING

Linear Programming based rounding is an important heuristic solution method. The idea LP-Rounding is to solve the linear relaxation rounding the fractional variables to recover integer feasible solutions of MILPs, trying to ensure that in the process the objective value does not deteriorate much (THANH; BOSTEL; PÉTON, 2010; BALL, 2011; MELO; NICKEL; SALDANHA-DA-GAMA, 2012). From a theoretical point of view, the quality of the linear relaxation depends mostly on how close the mathematical formulation is the representation of the original problem (BARROS, 1998). Ball (2011) states from a practical stand point, an LP Rounding solution is a natural and reasonable approach that introduces little error.

In our MILP model there are two types of integer variables in this problem: the first type is used to determine warehouse locations, while the second type is used to assign customers to warehouses. A natural layered structure occurs in this problem: we have to use the rounding to fix the warehouse locations first and then fix the assignment of customers to warehouses. If we fix the customer-warehouse assignment first, the corresponding warehouse is also fixed at the same time, which may result in poor solutions. The general structure of LP Rounding is outlined in Figure 6 as below.

Figure 6 - LP Rounding heuristic

Step 0: Initial Solution = Best Rounding Solution

Step 1: Randomly disable a given number of plants, warehouses and a percentage of arc that appear in the feasible solution from the last iteration

Step 2: Initialization. Solve the Linear Relaxation of MILP to generate an initial solution

Step 3: Locating the warehouses. Let F be the number of warehouse location variables. Set F = 0

- **Step 3.1:** Sort binary variables corresponding to the warehouse locations (a_w) in a non-increasing order
- **Step 3.2:** For all a_w
  - If a_w is almost 1 (say more than 0.95), fix it to 1, and set $F = F + 1$. If $F > U_w$ go to Step 4 (U_w is the given upper bound of warehouses). If $a_w < 0.95$, exit the loop.
- **Step 3.3:** If no a_w was fixed in Step 3.2, fix a_w with the biggest value being 1
- **Step 3.4:** With fixed a_w, solve the updated Linear Programming model again.

Step 4: Assign customers to warehouses. Let F be the number of customers that have been assigned. Set $F = 0$

- **Step 4.1:** Sort binary variables corresponding to the warehouse locations (g_{wc}) in a non-increasing order
- **Step 4.2:** For all g_{wc}
  - If g_{wc} is almost 1 (say more than 0.95), fix it to 1, and set $F = F + 1$. If all the customers are fixed, go to Step 4. If $g_{wc} < 0.95$, exit the loop
- **Step 4.3:** If no g_{wc} was fixed in Step 4.2, we attempt to fix the customer zone with the largest total demands. Fix it to the warehouse with the largest remaining capacity. Our purpose here is to keep the warehouse capacity violation as small as possible
- **Step 4.4:** With fixed g_{wc}, solve the updated Linear Programming model again

Step 5: If the given iteration is reached, output the best solution. Otherwise, go to Step 1.

Source: elaborated by author

The algorithm above outlines the LP Rounding method proposed. First, the LP relaxation of MILP is solved. Next, the warehouses are selected and a_w is fixed to 1 if biggest to 0.95. The maximum numbers of warehouses (U_w) need to be respected. The a_w is fixed and the LP relaxation is solved again.

Now, the customers (g_{wc}) are selected and fixed to 1 if biggest to 0.95. After to fix the customers, the LP relaxation is solved for the last time. If the solution is feasible, its assumes the initial solution in the new iteration. Before start the new initialization, the perturbation procedure (Step 1) disables randomly a number of plants, warehouses and a percentage of arc from initial solution to diversify the new solution.

The motivation for developing an LP Rounding heuristic stems from this being a natural approach to explore the structure and SCND problem and from the good lower bounds provided by the linear relaxation of model. According to Melo et al. (2014), a variety of facility location problems have been solved efficiently by LP-rounding techniques.

5.1.2 MULTI-START PROCEDURE

Metaheuristics are high-level solution methods that focus on strategies to avoid from local optima and perform a robust search of a solution space. Multi-start methods, appropriately designed, incorporate a powerful form of diversification. In this sense, multi-start procedures were originally conceived as a way to exploit a local or neighborhood search procedure, by simply applying it from multiple random initial solutions (MARTÍ; MARCOS MORENO-VEGA; DUARTE, 2010). The Multi-start procedure has played an important role in defining the best and most diversified solutions.

In order to implement the proposed heuristic approach efficiently, we developed a Multi-start method in the LP Rounding procedure. According to Martí, Marcos Moreno-Vega and Duarte (2010), the multi-start methods have two phases: the first one in which the solution is generated and the second one in which the solution is typically (but not necessarily) improved. Our Multi-start procedure suggests a perturbation process in the initial solution from a last iteration to obtain different solutions in each new iteration.

To generate a different initial solution, the perturbation procedure disables a percentage of arcs, based on parameters and random choices that appear in the initial solution from the last iteration and run the LP Rounding procedure. The same process is simultaneously utilized for plant and warehouse candidates specifying the number of plants and warehouses that are disabled to build a new solution.

The perturbation procedure disables some plants, warehouses and a certain percentage of warehouse/customer assignments in the previous solution to start an initial solution in a new iteration. This strategy allows exploring different solution spaces for feasible and good solutions found in the previous iterations.

Maybe one of the most important procedures to contribute to the good performance of Multi-start developed in this study is to define the best perturbation parameters, since these parameters allows obtaining a greater variability of neighborhoods to explore different solution spaces in a heuristic procedure. Thus, feasible solutions are found for each iteration with different sets of plants, warehouses and assignments.

As typical in heuristic development, tuning these parameters is a critical issue. Based on a number of computational experiments, in Chapter 6 we present the parameter settings that best contributed to a good performance of our Multi-start procedure.

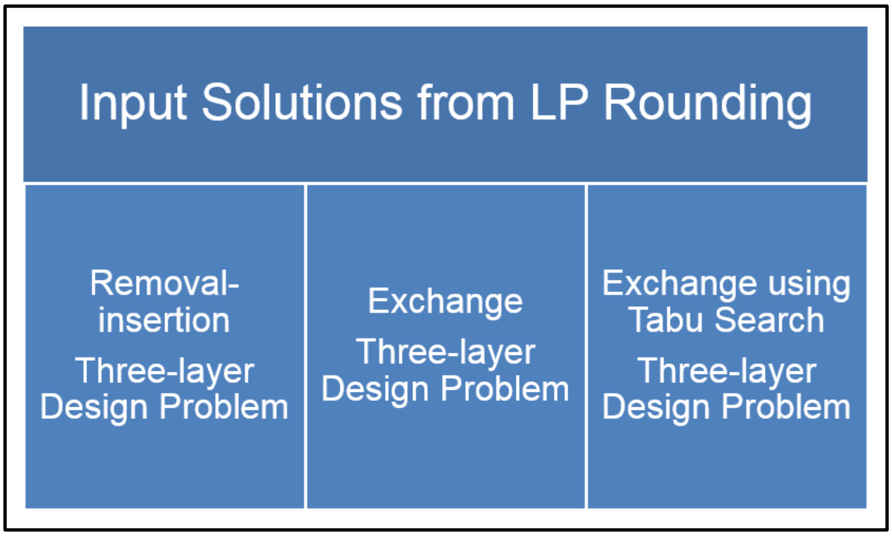
5. 2 Local Search Phase

Local Search is based on what is perhaps the oldest optimization method. The idea is so simple and natural and has proved its worth in a variety of difficult combinatorial optimizations problems. To apply this approach to a particular problem, we need to obtain an initial feasible solution. It is usual to execute a local search from several different starting points and to choose the best result. It is also to decide how many starting points to try, and how to distribute them. In the last step, we must choose a "good" neighbor for the problem at hand, and a method for search for it (PAPADIMITRIOU; STEIGLITZ, 1982).

The Local Search here is conducted at the customer level, trying to reassign customers in different warehouses. We do not adjust the locations of plants and warehouses, since their different locations are handled by different initial solutions from the LP based rounding heuristic.

For the design of efficient local search methods it is important to incorporate intensification as well as diversification phases into the search (MARTÍ; MARCOS MORENO-VEGA; DUARTE, 2010). Thus, we proposed two different strategies for Local Search operations: removal-insertion and exchange. This Local Search implementation was conducted in different steps. In first step, we developed a Removal-insertion Strategy, posteriorly the Three-layer Design Problem was solved. In second step, the Exchange Strategy was implemented and the results was obtained from Three-layer Design Problem. In last, the Exchange Strategy was developed using Tabu Search approach associated with Three-layer Design Problem solution. The Figure 7 shows the computational implementation of Local Search.

Figure 7 - Framework of computational implementation of Local Search



Source: elaborated by author

Details of both strategies procedures and implementations are described as follow.

5.2.1 REMOVAL-INSERTION STRATEGY

The Removal-insertion strategy is relatively simple. For each customer assigned to a warehouse, we examine if removing it from the current warehouse and assigning this customer in a different warehouse can reduce the total costs, without violation of capacity of the warehouse. If so, the removal and insertion operations are carried out. The basic Removal-insertion algorithm is outlined in Figure 8 as below.

Figure 8 - Removal-insertion algorithm

```
Step 0: Initial Solution = Best Rounding Solution
Step 1: Randomly permute the Customer Zones in $C$
Step 2: For each Customer Zone $c \in C$
    Step 2.1: For each candidate warehouse $c$ except the warehouse $w$ current
    assigned
```

```
        Step 2.1.1: Try to move $c$ from the current warehouse and insert it to $w$.
        If the capacity is not violated, determine the new total cost. Otherwise, go
        to Step 1
        Step 2.1.2: If the new total cost is less than the bet one, update the best
        one
    Step 2.2: If there exists the best new warehouse, remove $c$ and assign to the new
    warehouse
Step 3: Terminate if the stop iteration criteria (time) is satisfied. Otherwise, go to Step 1
```

Source: elaborated by author

In Step 1, we use random shuffle in the implementation. In Step 2.1, there are different implementations: First, we consider the warehouses selected in the initial solution; Second, we consider other warehouse if the total used is less than U_w. The first one is more straightforward and is implemented first.

In Step 2.1.1. where we (1) need to examine if the capacity of the target warehouse violated and (2) the need to solve a Three-layer design problem to determine the new cost. The details of Three-layer design problem modeling is shown in Section 5.2.3 that describes the successful implementation of Local Search using a Tabu Search technique.

5.2.2 EXCHANGE STRATEGY

In the exchange strategy, we try to exchange two customers assigned to different warehouses. For example, customer 1 is assigned to warehouse A, and customer 2 is assigned to warehouse B. We will see if the following will reduce the total costs: customer 1 is assigned to warehouse B and customer 2 is assigned to warehouse A. The basic Exchange algorithm is outlined in Figure 9.

Figure 9 - Exchange algorithm

```
Step 0: Initial Solution = Best Rounding Solution
```

```
Step 1: Randomly permute the Customer Zones in $C$
Step 2: For each Customer Zone $c1 \in C$
    Step 2.1: For each Customer Zone $c2 \in C$
        Step 2.1.1: If $c_1$ and $c_2$ are assigned to different warehouses and $c$ capacity is not violated, determine the new cost. If the new total cost is less than the best one, update the best customer. Let it be $c^*$.
    Step 2.2: If there $c^*$, exchange $c_1$ and $c^*$
Step 3: Terminate if the stop iteration criteria (time) is satisfied. Otherwise, go to Step 1
```

Source: elaborated by author

As was done in the Local Search with Removal-Insertion Strategy, the Transportation Problem is solved after the Local Search procedures to find the new total cost.

The results obtained by both Local Search strategy (removal-insert and exchange) were not satisfactory. In computational tests, the Local Search was performed over 12 hours for each strategy. The Local Search using the Exchange Strategy presented viable results, but with modest improvement in the objective function. In turn, the Removal-insertion implementation not improved the LP Rounding solution within 12 hours.

According to Martí, Moreno-Vega and Duarte (2010), the randomization is a very simple way of achieving diversification, but with no control over the diversity achieved since in some cases we can obtain very similar solutions. For this, it need developed some mechanisms to control the similarities in order to discard some solutions or generate the solutions in a deterministic way that guarantees a certain degree of difference. Thus, the random process in the choice of customers probably caused the unsatisfactory results obtained in the Removal-insert and Exchange. This random selection does not guarantee the best option to choose and exchange the customers assigned to different warehouses. Simultaneously, without criteria to select the best customers to the exchange procedure can avoid exploring different neighbors.

In order to overcome the unsatisfactory results of implementations previously described, we developed a Local Search with Exchange Strategy using

Tabu Search techniques as follow. In this step, the Exchange Strategy is maintained, but selection criteria's were incorporated in addition the random generation of choice.

5.2.3 EXCHANGE STRATEGY USING TABU SEARCH

Over the past two decades metaheuristics have become important tools for solving various combinatorial problems. Among the different existing metaheuristic methodologies, Tabu Search (Glover; Laguna, 1997) has become a very popular approach as it identifies high-quality solutions to many problems (MELO; NICKEL; SALDANHA-DA-GAMA, 2012). Tabu Search can be an efficient method in solve the network design problem. Among the metaheuristics, Tabu Search seems to fit to this model since the rules used has a tendency of the staying near from the current solution in developing the neighbor, hence getting out of the local optimum is the critical way to reach the better solution area (LEE; KWON, 2010). Although the Tabu Search literature is very rich, only a few papers address the application of this master strategy to solve facility location problems in the context of SCND (LEE; DONG, 2008; LEE; KWON, 2010; MELO; NICKEL; SALDANHA-DA-GAMA, 2012).

Our Tabu Search implementation was inspired in Lee and Kwon (2010). In their paper, the authors proposes four types of neighbor generation methods. In order to avoid repeating the exchange procedure between the same warehouses, our Tabu Search technique implemented guide the Local Search procedure to explore the different spaces of solutions. In this approach, the neighbor size is enlarged in an attempt to find a better solution.

The proposed short-term memory tabu search algorithm is characterized by a set of parameters:

- **Tabu List Size (*h*):** this parameter determines the size of the tabu list. The list size considers how many elements (arcs) will be stored in the list to check a possible exchange between warehouses. If the arc is on the list, then you cannot use it to carry out an exchange procedure. Thus, another arc that has not been recently used is selected for the exchange.

- **Maximum Number of Iterations (*i*):** this parameter defines the maximum number of iterations that the arcs remain on the list. When the arc remains consecutively on the list the maximum number of iterations defined in parameter, in the next iteration this arc is excluded from the list. This procedure allows exploring other neighbor spaces and finding a greater variability of solutions.
- **Computational Time (*t*):** define how many seconds the exchange procedure will be applied in the Local Search Phase.

We present in Chapter 6 the parameter settings of the Tabu Search operations. The best set of parameters was established based on the tests carried out in the implementation and computational experiments phase. The Exchange Strategy using a Tabu Search techniques is outlined in Figure 10.

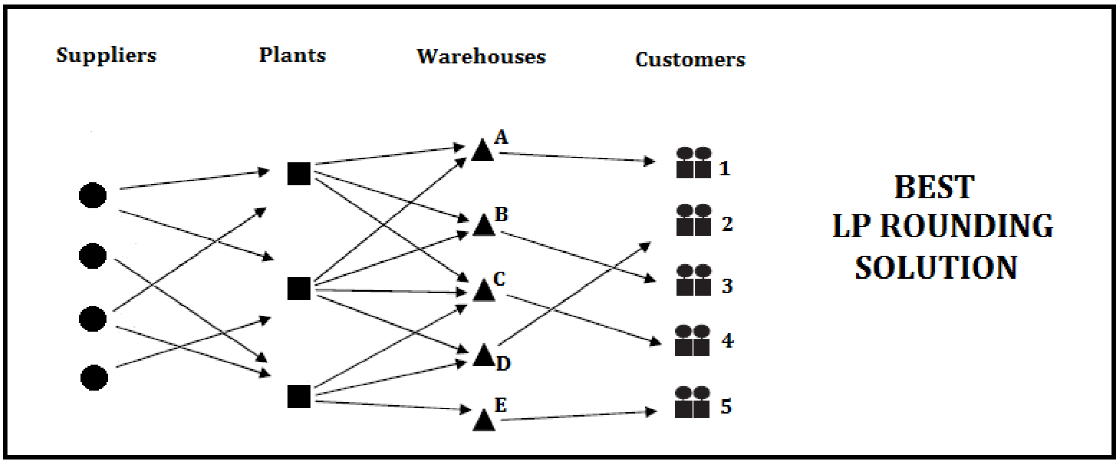
Figure 10 - Exchange using tabu search algorithm

```
Step 0: Initial Solution = Best Rounding Solution
Step 1: Randomly permute the Customer Zones in $C$
Step 2: For each Customer Zone $c1 \in C$
    Step 2.1: For each Customer Zone $c_2 \in C$
        Step 2.1.1: If $c_1$ and $c_2$ are assigned to different warehouses and capacity is
                    not violated go to Step 2.1.2. Otherwise go to Step 1
        Step 2.1.2. If the arc is not on the tabu list, update tabu list and solve the
                    Transportation Problem to determine the new cost. Otherwise go to Step 1
    Step 2.2 Determine total cost, if total cost is less than the best solution then update
             best solution = total cost
Step 3: Terminate if the stop iteration criteria (time) is satisfied. Otherwise, go to Step 1
```

Source: elaborated by author

In the first step the initial solution for a Local Search procedure is the best rounding solution found in the aforementioned LP Rounding heuristic. The SCND structure for best LP Rounding solution is shown in Figure 11.

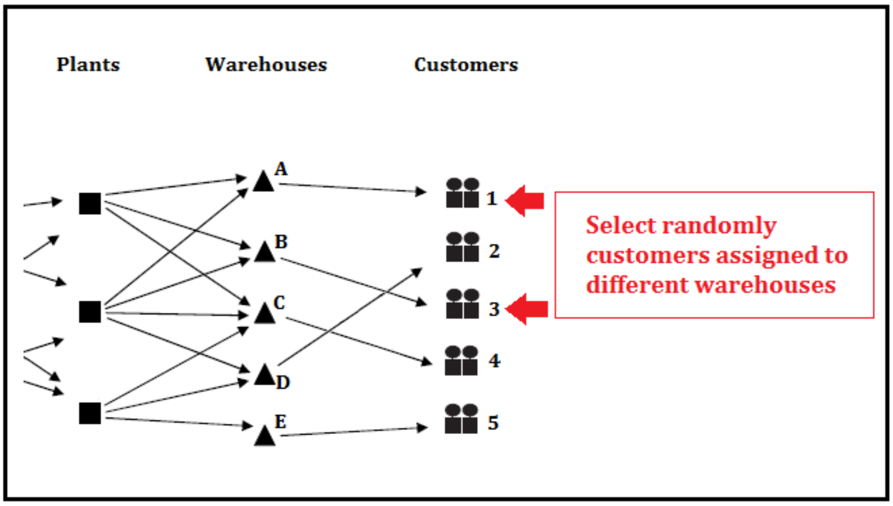
Figure 11 - SCND best LP Rounding solution



Source: elaborated by author

In Step 1, we try to randomly exchange two customers assigned to different warehouses. The following Figure 12 illustrates the random selection of two customer zones assigned to different DCs.

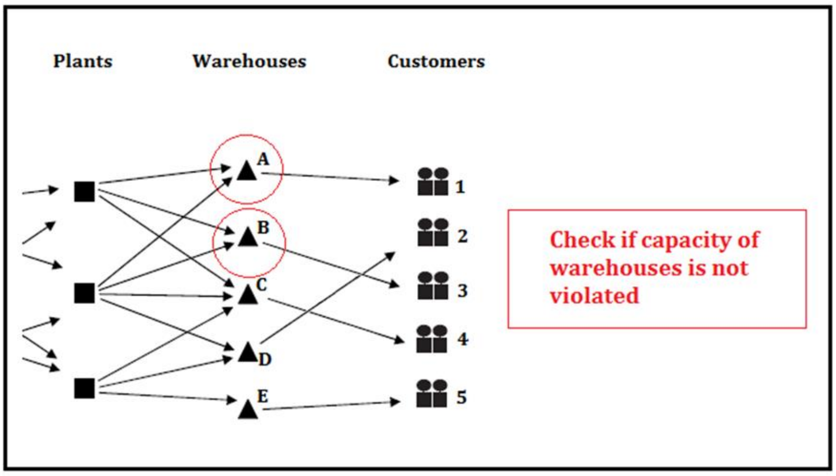
Figure 12 - Select randomly customer zones



Source: elaborated by author

In Step 2 and Step 2.1 we consider each customer zone assigned in the warehouses selected in the initial solution. The key is in Step 2.1.1, where we need to examine if the customer zones selected to exchange are assigned to different warehouses and if the capacity of the target warehouse is not violated. The Figure 13 illustrates the checking of warehouses capacities.

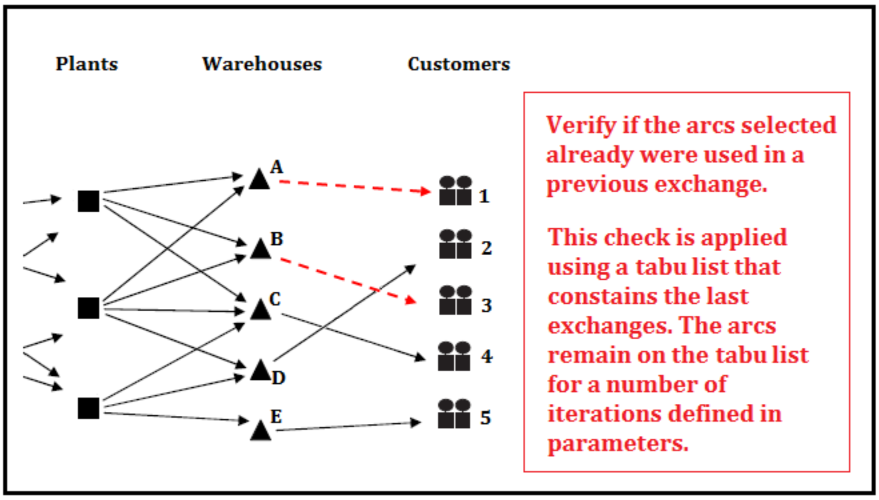
Figure 13 - Checking the warehouse capacities



Fonte: Prepared by the author

In the Step 2.1.2 the Tabu Search technique is applied considering if the exchange arc selected has been used in a previous exchange. In this step is checked if the arc is not on the tabu list. If arc is not in the tabu list, the exchange of the selected arc is allowed and this arc is added into the tabu list removing the oldest arc. If the arc had already been used in a recent exchange go to Step 1. The Figure 14 illustrates the Tabu Search procedures in this step.

Figure 14 - Verifying arc on the tabu list



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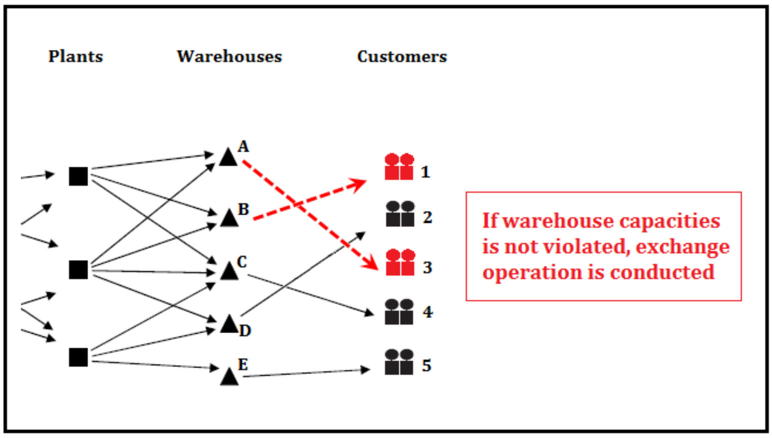
In this case, if an exchange is possible without violating the warehouse capacities, the exchange is conducted as shown in Figure 15 and the Linear Programming Transportation Problem is run to determine the new cost.

Figure 15 - Exchange the customers from original warehouses



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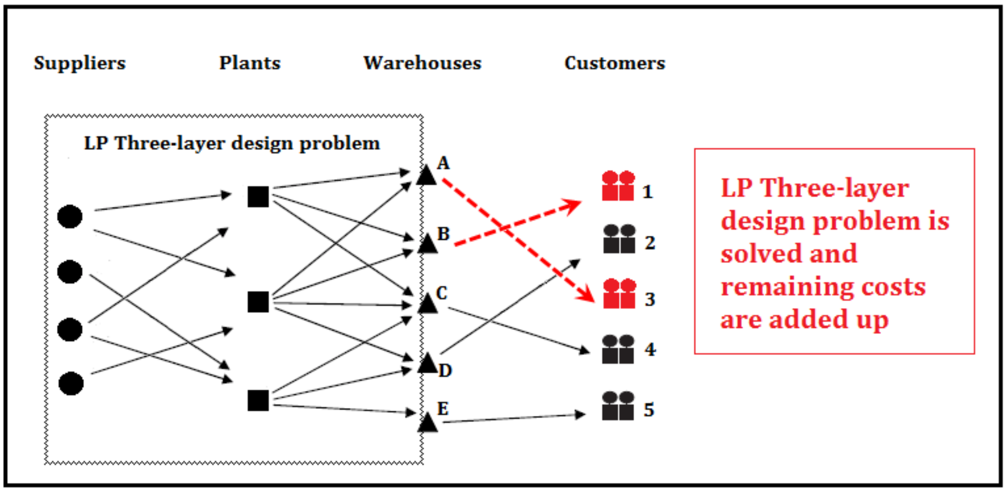
Step 2.1.2 following the Linear Programming Three-Layer Design Problem is solved and we determine if the total cost is less than the initial solution as illustrated in Figure 16.

Figure 16 - LP Three-layer design problem is solved



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After Linear Programming is solved, the remaining costs need to be added up. For this, it is necessary to add it on the objective function the throughput warehouses costs, transportation costs from warehouse to customer zones and fixed warehouse costs according to the configuration proposed for the local search procedures. In the last one, the procedure is terminated when the stop criteria are finalized.

5.2.4 THREE-LAYER DESIGN PROBLEM

The Three-Layer Design Problem is modeled as a Linear Programming (LP) problem. In the transportation problem, the demands in each warehouse need to be updated to consider the current assignment. Note that in the following, g_{wc} is constant, which is known from the local search. The demand at each warehouse is known. So, the following problem considers (1) sending materials from supplier to plants, (2) sending products from plants to warehouses, and (3) production costs at the plants.

Due to the small number of suppliers and plants involved in the Three-layer design problem, this problem it is not so complex to solve. Thus, its solution can be easily obtained by a powerful commercial package in reasonable time.

Three-Layer Design Problem (P)

Function Objective

$$\min \sum_{f \in F} CT_f^o \, b_f + \sum_{f \in F} \sum_{w \in W} \sum_{s \in S} CT_{fs}^p \, z_{fw}^s + \sum_{f \in F} \sum_{r \in R} \sum_{v \in V} CT_{fvr}^t \, y_{vf}^r + \sum_{f \in F} \sum_{w \in W} \sum_{s \in S} CT_{fws}^t \, z_{fw}^s \qquad (5a)$$

s.t.

$$\sum_{c \in C} d_{cs} g_{wc} \leq \sum_{f \in F} z_{fw}^s \qquad \forall\, s \in S, \forall\, w \in W \qquad (5b)$$

$$\sum_{f \in F} y_{vfr} \leq CAP_{vr} \qquad \forall\, r \in R, \forall\, v \in V \qquad (5c)$$

$$\sum_{w \in W} \sum_{s \in S} u_{rs} z_{fw}^{s} \leq \sum_{v \in V} y_{vf}^{r} \qquad \forall\, r \in R, \forall\, f \in F \qquad (5d)$$

$$\sum_{w \in W} \sum_{s \in S} u_s\, z_{fw}^{s} \leq CAP_f\, b_f \qquad \forall\, f \in F \qquad (5e)$$

$$\sum_{f \in F} b_f \leq U_f \qquad (5f)$$

$$b_f = \{0,1\} \qquad \forall\, f \in F \qquad (5g)$$

$$g_{wc} = \{0,1\} \qquad \forall\, w \in W, \forall\, c \in C \qquad (5h)$$

$$z_{fw}^{s}, y_{vf}^{r}, o_w \geq 0 \qquad \forall\, r \in R, v \in V, f \in F, s \in S, w \in W \ (5i)$$

Throughput costs at warehouse, transportation costs from warehouses to customer zones, and warehouse fixed costs are known and can be determined beforehand. After the following LP is solved, these remaining costs need to be added up. In this way, we will have the overall costs after the Local Search approach is applied using an exchange strategy.

The Local Search phase is basically oriented to identifying good quality feasible solutions from LP Rounding solutions computing time criteria according to parameters defined previously have not been achieved. The values of these parameters (tabu list size, maximum numbers of iterations and computational time) are defined from preliminary exploratory tests considering the improvement of results.

6 IMPLEMENTING AND COMPUTATIONAL EXPERIMENTS

In this chapter we report the results of the computational experience obtained over some randomly generated instances. The formulations and algorithms described in the previous sections has been implemented in C++ code language using the optimization engine COIN-OR (Computational Infrastructure for Operations Research) to solve the MILP related model.

The computational experiments and validation were carried out on a Dell Precision T3600 Server using Intel® Xeon® CPU ES5-1603 with 2.80 GHz and 16 GB RAM in the LINUX UBUNTU 14.04 LTS operational system. Below we introduce the computational tests and the numerical results analysis.

6. 1 Benchmark Instances and Test Problems

Test problems considering large instances associated with a four-echelon network were randomly generated to capture realistic characteristics. The verification and validation tests were performed using a set of 25 instances varying in size depicting a wide variety of instances close to real-life problems. In order to balance easy and difficult instances, when generating the instance sets, we followed the structure and sizes of different authors. The details of the main studies found in the literature review from which the experimental instances are derived are given in Table 1.

Table 1 - Benchmark instances in a literature review

#	Authors (Papers)	Vendors (Suppliers)	Raw Materials	Plants (Factories)	Warehouses (DCs)	Products (Groups)	Customers (Clients)
1	Geoffrion and Graves (1974)	-	-	14	45	17	127
2	Pooley (1994)	-	-	10	13	6	48
3	Camm et al. (1997)	-	-	60	17	50	130
4	Jayaraman and Pirkul (2001)	2	2	10	30	5	150
5	Vidal and Goetschalckx (2001)	50	35	8	10	12	80
6	Jang et al. (2002)	-	-	15	20	10	10
7	Melo et al. (2005)	-	-	5	20	10	150
8	Li et al. (2009)	-	-	70	105	40	175
9	Lee and Kwon (2010)	-	-	10	20	5	80
10	Thanh et al. (2012)	27	-	22	13	18	270

Source: elaborated by author

Note that some authors consider three or four echelon networks and different types of products or set (groups) of products in the supply chain network. According to the number of echelons and products the problem becomes more difficult to solve, especially when the number of warehouses and customers is high.

Several instances representing supply chain network structures were generated for evaluation with respect to number of suppliers, raw materials, plants, warehouses, customer zones and products. They are shown in Table 2. All instances are associated with a four-echelon network similar or larger than instances researched in the literature review.

Table 2 - Characteristic and sizes of instances

#	Suppliers	Raw Material	Plants	DCs	Products	Customer Zones	Amount Products
1	5	5	3	10	5	150	1,000,000
2	5	5	3	20	5	150	1,000,000
3	5	5	3	30	5	150	1,000,000
4	5	5	3	40	5	150	1,072,388
5	5	5	3	50	5	150	1,000,000
6	5	5	3	10	10	150	1,575,000
7	5	5	3	10	40	150	750,982
8	5	5	3	10	100	150	1,583,100
9	5	5	3	20	10	150	1,237,500
10	5	5	3	30	10	150	1,575,000
11	5	5	3	40	10	150	1,575,000
12	5	5	3	50	10	150	1,575,000
13	5	5	3	20	10	150	3,000,600
14	5	5	3	20	50	150	3,152,400
15	10	10	5	10	40	150	1,576,200
16	10	10	5	10	150	250	1,552,062
17	10	10	5	20	150	250	1,552,062
18	10	10	5	10	5	150	1,509,505
19	5	5	3	5	150	250	1,509,505
20	25	25	20	15	20	270	1,351,892
21	20	20	20	10	15	200	750,128
22	15	15	10	5	10	150	374,556
23	20	20	5	5	170	300	4,879,009
24	5	3	1	5	3	250	5,611,652
25	5	5	3	30	5	100	680,000

Source: elaborated by author

In addition, the amount of products involved in the problem is shown (this information is often not mentioned in the literature review). The structure cost has operational fixed costs and production and transportation costs associated with the capacity of plants and warehouses. Every instance has been checked as being feasible and solved independently in order to compare the performance of the approach proposed to solve it.

6. 2 Experimental Procedures

We describe the Construction Phase procedure to find feasible solutions applying the LP Rounding procedure considering a set of empirical experiments. The LP Rounding processing is based on procedures to identify the best set of plant and warehouses to compose the supply chain. The Local Search Phase is applied to improve the best feasible solution using the exchange strategy and Tabu Search technique as explained previously.

As described in the previous chapters, the First Step is to find the Lower Bound (LB) for Linear Programming Relaxation. After identifying the Lower Bound, the set of plants and warehouses must be found for the lowest LP-gap (The GAP found in the Construction Phase is called “LP-gap”) from the optimal Linear Programming solution. For this, it is necessary to test the LP Rounding procedure with different numbers of plants and warehouses to find a lowest LP-gap. In first step, the running LP Rounding is applied limited to 10 iterations.

The Second Step is to define the appropriate parameters for Perturbation procedure. These parameters are responsible for efficient Multi-start operation. The Perturbation procedure disables plants, warehouses and a percentage of arcs that appear in initial solution from the last iteration. In the experimental tests we disabled 1 to 2 plants. The limited number of plants does not recommend making this parameter very large. In turn, the DC number that should be disabled in the initial solution is defined as between 2 and 3 DCs. The percentage arcs disabled in the experimental tests were from 20% and 35%. This percentage cannot be too large to preserve the main choices of the initial solutions. The setting parameters in the perturbation procedure were changed according the size of each experimental instance, respecting these ranges.

Third Step is to run 200 iterations of an LP Rounding procedure using the set of plants and warehouses and perturbation parameters defined when the best Upper Bound was found. In the exploratory tests, increasing numbers of iterations give good results and different configurations of solutions. This procedure allows exploring a larger solution space by diversifying initial solutions for each iteration in the LP Rounding procedure. In this step, the 50 best solutions obtained by LP Rounding procedure for each instance are classified and analyzed according to the results obtained.

In this Last Step, from 50 best solutions obtained, the best LP Rounding solution of each instance (lower LP-gap) is submitted to the Local Search procedure based on Exchange Strategy using a Tabu Search short-term memory technique. In the Local Search phase the exchange procedure is applied using a Tabu Search according to parameters settings defined below.

The Tabu List Size *(h)* value was defined as 50 elements and the Maximum Number of Iterations *(i)* values was 10 iterations. The Computational Time *(t)* value was established as 7.200 seconds. The stop time criteria are lower and similar to the computational time found in the literature review (THANH et al., 2012, MELO et al., 2014).

Exploratory testing to find good ranges of parameters were carried out by running the Local Search with a variety of parameter settings. The selected parameters ensure a good compromise between the quality of the solution and the reasonable computation time.

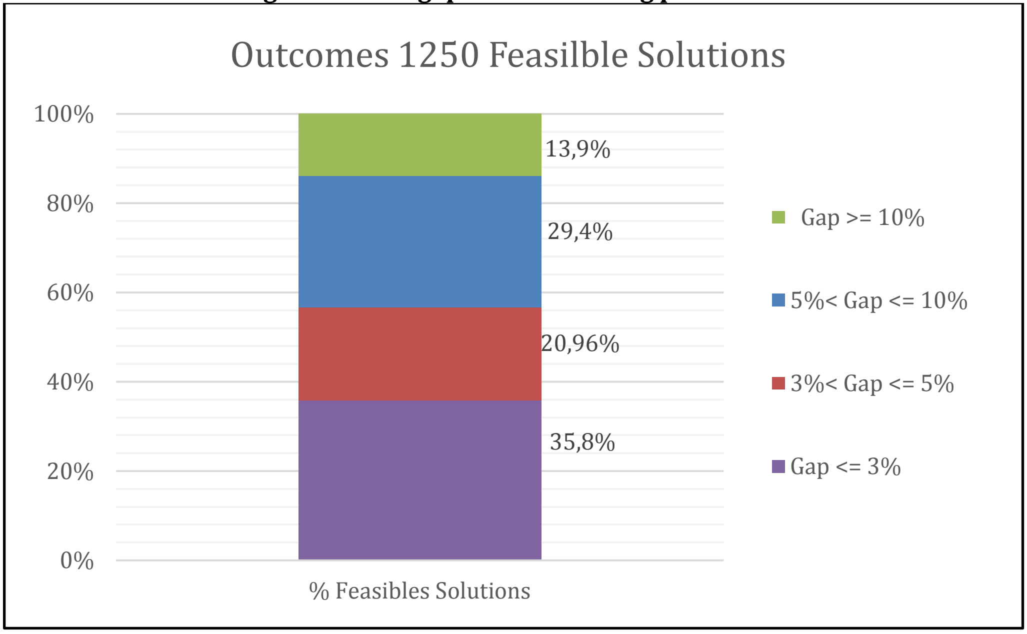
6. 3 Summary of Results

In this section, we evaluated the performance of the new heuristic approach for SCND using the 25 instances described above.

In the Construction Phase, the top 50 results for each instance totaling 1.250 feasible solutions were analyzed in detail below. Considering 200 iterations in the LP Rounding procedure the computation times varied from 480 to 4.020 seconds. However, most instances are solved in less than 1800 seconds (30 minutes), the exceptions being the instances with a large number of warehouses, products and customers. In general, solution times were low (less than 120 seconds) to solve every instance considering 10 iterations in the LP Rounding procedure proposed.

Figure 17 illustrates the outcomes of LP Rounding heuristic procedures from 1250 rounding solutions. The solutions are grouped into four categories according to the LP-gap. The LP-gap values considered in this study are calculated as **(UB - LB)/LB .100** with the Upper Bound denoting the objective value of the best feasible solution and the Lower Bound is the optimal Linear Programming value.

Figure 17 - LP-gap in LP Rounding procedure



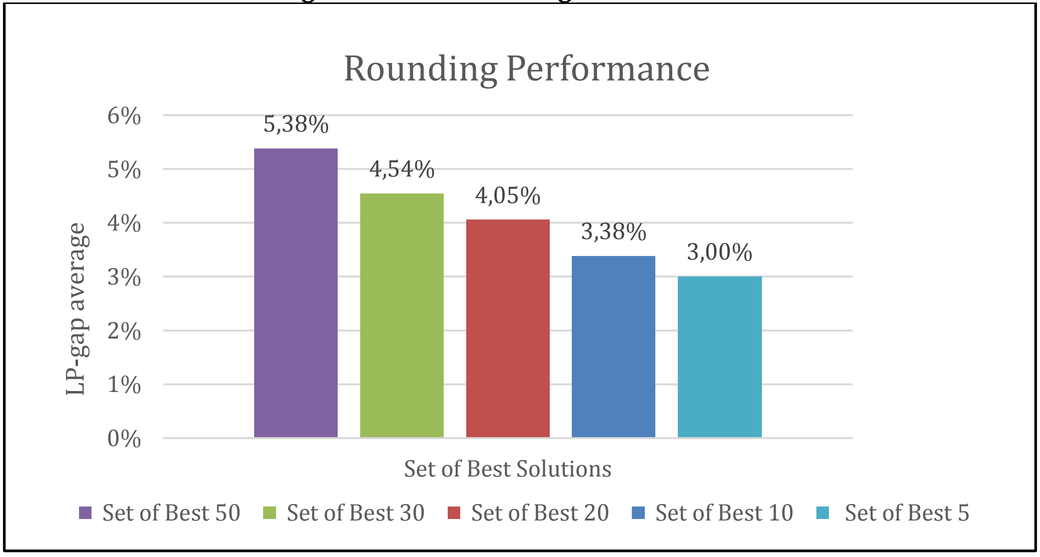
Source: elaborated by author

Over 86% of these results have feasible solutions below 10% compared to Lower Bound. The result of this is that 29.4% solutions have a LP-gap between 5 and 10%. The effectiveness of the LP-Rounding is demonstrated by the high quality of the best solutions identified, which have an LP-gap below 5% in 710 out of 1250 solutions (56.76%).

Analyzing the grouping of the best results obtained in the Rounding procedure, almost 36% of the solutions have an LP-gap less than 3%. It shows that the LP Rounding heuristic provides solutions within an acceptable optimality range considering a reasonable set of large instances.

Considering the top 50 solutions, we analyzed the best average LP-gap solutions of each instance. We summarize five groups of average LP-gap: best 50, 30, 20, 10 and 5 solutions in Figure 18.

Figure 18 - Set of average best solutions



Source: elaborated by author

As shown in Figure 18, the best 50 solutions of each instance represent the average LP-gap of 5.38% compared to the Lower Bound result. Likewise, the set of top 30 solutions reduces the LP-gap by almost 1 percentage point comparing to the LP-gap of the set top 50 solutions. The set top 20 and top 10 have an average LP-gap of 4.05% and 3.38%, respectively. Finally, Figure 18 shows that percentage of the 10 best solutions has a LP-gap less than 4% compared with the LB Relaxation solutions.

Below we present some analysis of results and behavior of the LP-Rounding procedure in the experimental tests. Nonetheless, the detailed results of the rounding heuristic application can be found in Appendix A.

Table 3 reveals that the Construction Phase (LP Rounding) procedure delivers solutions with acceptable results for a four-echelon network. The total number of iterations performed by the LP Rounding in each instance is shown in column 3.

Table 3 - Summary of computational results – LP ROUNDING

Instances #	Lower Bound (OF)	Solutions of 200 iterations			Top 50 Solutions		Best Solutions	
		Feasible Solutions	**Average UB (OF)**	**Average LP-gap**	**Average UB (OF)**	**Average LP -gap**	**Upper Bound**	**LP gap**
Inst01	16,592	158	19,431	17.11%	18,876	13.76%	17,215	3.76%
Inst02	16,101	166	18,956	17.73%	18,417	14.38%	16,718	3.83%
Inst03	15,018	179	17,278	15.05%	15,959	6.27%	15,317	1.99%
Inst04	19,048	155	21,,196	11.28%	20,224	6.18%	19,615	2.98%
Inst05	16,882	156	18,,585	10.08%	18,121	7.34%	17,081	1.18%
Inst06	30,235	149	32,492	7.46%	32,149	6.33%	31,499	4.18%
Inst07	12,785	112	13,243	3.58%	13,235	3.52%	13,176	3.06%
Inst08	28,715	144	31,357	9.20%	30,620	6.64%	29,228	1.79%
Inst09	25,691	121	27,111	5.53%	26,696	3.91%	25,807	0.45%
Inst10	27,442	127	30,480	11.07%	29,939	9.10%	27,992	2.00%
Inst11	30,697	119	32,514	5.92%	31,845	3.74%	31,007	1.01%
Inst12	19,707	114	21,177	7.46%	20,801	5.55%	19,781	0.37%
Inst13	61,288	177	63,148	3.03%	63,061	2.89%	62,675	2.26%
Inst14	60,023	164	63,712	6.15%	63,518	5.82%	61,865	3.07%
Inst15	14,048	131	14,418	2.64%	14,303	1.82%	14,261	1.51%
Inst16	34,777	134	36,532	5.05%	35,614	2.41%	35,183	1.17%
Inst17	34,497	188	37,401	8.42%	37,124	7.62%	35,864	3.96%
Inst18	17,832	154	20,447	14.66%	19,535	9.55%	18,393	3.15%
Inst19	31,716	105	33,421	5.38%	32,996	4.04%	32,952	3.90%
Inst20	37,488	167	39,550	5.50%	38,914	3.80%	38,599	2.96%
Inst21	20,129	157	21,088	4.76%	20,549	2.09%	20,226	0.48%
Inst22	86,85	184	10,146	16.82%	88,09	1.43%	87,62	0.89%
Inst23	124,587	199	125,641	0.85%	125,605	0.82%	125,490	0.72%
Inst24	86,783	200	89,197	2.78%	887,16	2.23%	88,617	2.11%
Inst25	11,922	133	13,079	9.70%	121,92	2.26%	12,146	1.87%
			Average	**8.29%**	**Average**	**5.34%**	**Average**	**2.19%**

Source: elaborated by author

When the instances were exposed to run 200 iterations, we can observe practically 73% of success rate in obtaining viable solutions in LP Rounding procedure proposed. In practice, this means that the heuristic approach proposed provides almost 75% of reasonable solutions considering the average LP-gap as 8.29%. This underlines the efficiency of the LP Rounding procedure.

Columns 2, 4, 6 and 8 present the objective functions values (in thousands) of the feasible solutions identified for each instance in the LP Rounding procedure. Considering these values, the LP-gap is shown in columns 5, 7 and 9. In columns 5 and 7 is shown the average LP-gap for 200 iterations and top 50 solutions, respectively. As described previously, the LP-gap is defined as (Upper Bound-Lower Bound)/Lower Bound multiplied by 100%. Column 9 gives the LP-gap between the objective function value of the best solution identified by LP Rounding and the value of the Lower Bound (Linear Programming solution). As shown int Table 3, 8 instances (32%) give an LP-gap between 1% and 2% and 12 instances (48%) present the LP-gaps between 2% and 4.18%. The effectiveness of the LP Rounding heuristic is denoted by the high quality of the best solutions identified, which have an LP-gap below 1% in 5 out of 25 instances (20%). Regarding the best solution of all 25 instances by LP Rounding, the average LP-gap is 2.19%.

According to the results presented, the Construction Phase managed to identify good feasible solutions from the LP Rounding procedure. In the next phase, the best LP Rounding solution of each instance is used as initial solutions for the Local Search Phase.

In the second phase, the Local Search procedure seeks to improve the initial solution by exchange strategy using the Tabu Search technique approach. The Tabu Search parameters settings (tabu list size and maximum numbers of iterations) were described in the Section 6.2 aforementioned. In this procedure, the best LP Rounding solution in each instance is submitted to the Local Search procedure for 7.200 seconds. As described previously, the customer zones assignment in different warehouses is exchanged and the new costs are evaluated. The Tabu Search technique allows exploring different neighborhood spaces and increasing the variability of solutions. The neighborhood size is enlarged in an attempt to find a better solution for each instance respecting the parameters defined. In order to evaluate the benefit of the new heuristic approach proposed, the Local Search results are compared with the best LP Rounding solutions considering the respective GAPs of each instance as show Table 4 following.

Table 4 - LP Rounding GAP x Local Search GAP

Instances	**Instance sizes**							**LP Rounding**		**Local Search**	
#	**Supply**	**Raw**	**Plant**	**DC**	**Products**	**CZ**	**LB**	**UB**	**LP gap**	**UB**	**LS**
Inst1	5	5	3	10	5	150	16,592	17,216	3.76%	17,080	2.94%
Inst2	5	5	3	20	5	150	16,101	16,719	3.83%	16,593	3.05%
Inst3	5	5	3	30	5	150	15,018	15,317	1.99%	15,282	1.75%
Inst4	5	5	3	40	5	150	19,048	19,616	2.98%	19,519	2.47%
Inst5	5	5	3	50	5	150	16,883	17,081	1.18%	17,045	0.96%
Inst6	5	5	3	10	10	150	30,236	31,499	4.18%	31,357	3.71%
Inst7	5	5	3	10	40	150	12,786	13,177	3.06%	13,172	3.02%
Inst8	5	5	3	10	100	150	28,716	29,229	1.79%	29,191	1.65%
Inst9	5	5	3	20	10	150	25,692	25,808	0.45%	25,782	0.35%
Inst10	5	5	3	30	10	150	27,442	27,992	2.00%	27,810	1.34%
Inst11	5	5	3	40	10	150	30,698	31,007	1.01%	30,930	0.76%
Inst12	5	5	3	50	10	150	19,708	19,782	0.37%	19,782	0.37%
Inst13	5	5	3	20	10	150	61,288	62,675	2.26%	62,617	2.17%
Inst14	5	5	3	20	50	150	60,024	61,865	3.07%	61,448	2.37%
Inst15	10	10	5	10	40	150	14,048	14,261	1.51%	14,248	1.42%
Inst16	10	10	5	10	150	250	34,777	35,183	1.17%	35,181	1.16%
Inst17	10	10	5	20	150	250	34,497	35,864	3.96%	35,853	3.93%
Inst18	10	10	5	10	5	150	17,832	18,393	3.15%	18,345	2.88%
Inst19	5	5	3	5	150	250	31,716	32,953	3.90%	32,952	3.90%
Inst20	25	25	20	15	20	270	37,489	38,599	2.96%	38,566	2.88%
Inst21	20	20	20	10	15	200	20,129	20,226	0.48%	20,225	0.47%
Inst22	15	15	10	5	10	150	8,685	8,762	0.89%	8,761	0.87%
Inst23	20	20	5	5	170	300	124,58	125,490	0.72%	125,477	0.71%
Inst24	5	3	1	5	3	250	86,784	88,617	2.11%	88,580	2.07%
Inst25	5	5	3	30	5	100	11,923	12,146	1.87%	12,128	1.72%
								Average	**2.19%**	**Average**	**1.96%**

Source: elaborated by author

We call the Local Search GAP as "LS-Gap" for comparison with LP-Gap. However, the LS-Gap can be considered the real GAP of the heuristic approach proposed.

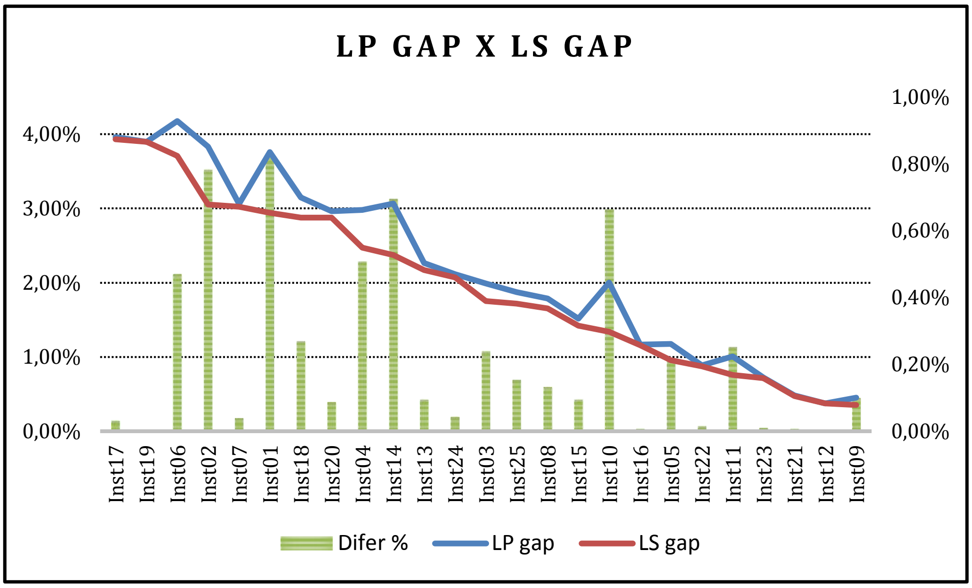
Table 4 displays the quality of the feasible solutions identified by the Local Search procedure. The Local Search improved 24 out of 25 instances (96%). The Local Search just cannot improve the Instance 12 that was the lowest LP-gap (0.375%) in the Construction Phase. Considering the initial solution from LP Rounding, the smallest improvement was observed in the Instance 19 with just 0.003%. On the other hand, the Instance 1 obtained an improvement of 0.79% from LP Rounding solution.

In particular, instances with 150 products and 250 customer zones (e.g. Instances 17 and 19) have the higher LS-gap and lower improvement after applied the Local Search procedure. However, it was unclear whether the size of instances influence the results because some instances with a large number of warehouses, products and customers zones (e.g. Instances 3, 4 and 8) have good solutions.

A further observation concerns the large LS-gaps that the solutions obtained by the new heuristic approach exhibit in five instances (Inst2, Inst6, Inst7, Inst17 and Inst19). In these solutions, the LP-gaps were above than 3.00% and between 3.02% and 3.92%.

Figure 19 illustrates the Local Search performance considering the LP-gap and the percentage improvement obtained in each instance. The horizontal axis represents each instances. The left vertical axis represents the percentage gap obtained in the LP Rounding and Local Search procedures. The right vertical axis (bargraph) represents the difference between LP-gap and LS-gap.

Figure 19 - LP Gap versus LS Gap



Fonte: Prepared by the author

The effectiveness of the Local Search heuristic is demonstrated by the high quality of the best solutions identified, which have an average LS-gap of 1.96% as shown in Table 4 in column 12. Moreover, in more than half of the instances (13 out of 25) the best solution is lower than 1.75% from LB solution. LP-gaps ranging from 1.16% and 1.75% were reported in 6 instances (24%). Local Search defines a feasible solution within 1% of optimality in 28% of the test problems (7 out of 25 instances).

The numerical results show that the new procedure performs well and can reach solutions within 0.47% of the linear relaxation bound (e.g. Instances 9, 12 and 21). Table 14 in Appendix A lists the main information and results of heuristic application in the 25 generated instances.

Large LS-gaps were also obtained for some of the instances with more customers zones. One possible explanation for this fact has to do with the impact that the number of integer variables on the problem. In fact, the number of integer variables depends on the number of warehouses and customer zones.

Computational implementation shows that the solution method proposed obtained satisfactory results when compared to the literature review. Table 5 below describes the details and the results of the test instances considered a benchmark in this research.

Table 5 - Review literature instances

Authors	Size	Suppliers	Raw materials	Plants	DCs	Products	Customers	Instances Tested	Echelons	Average Gap %	Min Gap %
Vidal and Goetschalckx (2001)	small	11	10	3	8	5	20	5	4	3.784	0.013
Vidal and Goetschalckx (2001)	medium	50	35	8	10	12	80	5	4	1.537	0.022
Jayaraman and Pirkul (2001)	large	3	2	10	30	5	150	5	4	2.71	1.560
Jayaraman and Pirkul (2001)	medium	2	2	5	30	10	75	10	4	2.01	1.020
Lee and Kwon (2010)	small	-	-	5	10	5	30	12	3	3.11	0.000
Lee and Kwon (2010)	large	-	-	10	20	80	30	12	3	3.95	0.000
Thanh et al. (2012)	large	27	27	22	13	18	270	15	4	0.96	0.200
Melo et al. (2014)	large	-	-	5	30	5	200	117	3	8.39	0.010
								Average		**3.306**	**0.353**

Source: elaborated by author

The size instances shown in column 3 correspond to own category by the author in their respective paper. Column 9 shows the number of tests carried out in each instance and column 10 show the number of echelons in the supply chain network. Table 13 showed the largest instance described in each category in the respective paper.

The heuristic approach proposed in this thesis had an average gap of 1.96% and a gap ranged between 0.352% and 3.931% for 25 experimental instances. Thus, considering the experimental tests shown in Table 4, the heuristic approach proposed obtained an average gap less than the average gap of the literature review (1.96% versus 3.306%). In addition, in our heuristic approach the computational experiments were faced with large scale instances with at least 150 customer zones and four layers. In turn, some authors present experimental instances with three echelons (LEE; KWON, 2010; MELO et al., 2014).

When we compare our results with the results found by Thanh et al. (2012), we are at a small disadvantage because of their excellent computational results. However, it stands out that, except for Lee and Kwon (2010), all authors consider computational test instances with less than 20 products. This fact implies less complexity for solving the supply chain problems. In the experimental instances of similar sizes (Inst32 and Inst35) presented in Thanh et al. (2012), our heuristic approach carried out an average gap of 0.594%. Therefore, our computational implementation shows satisfactory results with very close gaps between LB solutions and the literature review for large instances.

Considering these results, we realize that the new heuristic provides solutions within an acceptable optimality range for large scale instances in reasonable computational time.

In this chapter, we present the procedures to computational implementation of the heuristic approach proposed in this thesis. In additional, computational experiments on realistically sized generated instances were tested and the results were analyzed. In next chapter, we implement the heuristic approach in a realistic case from a multicommodity industry.

7 REALISTIC APPLICATION CASE

Companies today are faced with a competitive environment which involves challenges, such as how fast products are designed, manufactured and distributed, while simultaneously having to consider improving production efficiency and total operational cost (PAN; NAGI, 2013).

Farahani et al. (2014) state that clearly the existing models of SCND are not applicable in today's fiercely competitive markets and they should be extended to be adaptable to the competitive business environment. However, some studies have extended its scope implementation showing that companies have relied on optimization techniques for decision support when planning their logistics operations (GEOFFRION; GRAVES, 1974; POOLEY, 1994; CAMM et al., 1997; JAYARAMAN; PIRKUL, 2001).

In this respect, seeking to expand the contribution of this research, in this chapter we present the practical application of a heuristic approach proposed in the “real-world” context.

The modeling and solution procedure developed in this study were applied in the realistic context of a Brazilian company which is one of the biggest producers and distributors of tires in the country, with a highly influential market-share in South America.

The **Tire Company** is responsible for producing and distribution tires and other consumer products whose main raw material is rubber. Although it is a multinational operation, the focus of this application case is limited to the domestic market. This company, called Tires Company is fictitious, but refers to an existing enterprise that needs to redesign the distribution network configuration.

In this realistic context, the company aims to redesign its logistics project integrating four levels in the supply chain network operation. The scenario consists in selecting the suppliers of the main raw materials, determining the production flow in each plant, and deciding which candidate warehouses (distribution centers) should be opened. In addition, plant and warehouse capacities cannot be violated and the demand requirement for the products imposed by the customer zones needs to be fully satisfied.

In the next section, we present the steps carried out to implement the model proposed in this thesis for the realistic case study.

7.1 Preliminary Survey Costs

A preliminary study was conducted to survey the information relating to transport costs, production costs and demands of each product in the customer zones. To apply the heuristic approach proposed in this realistic case study, it was necessary to structure the network informations. For this, we need to collect, define and estimate the data from different sources considering real and reliable information.

The transportation costs from the suppliers to factories, factories to warehouses, and warehouses to customer zones were defined using data in the real context. The transport costs were estimated according to preliminary information considering the real freight costs using road transport (trucks). Thus, transportation costs are determined proportionally according to tire size and distance (in kilometers) between facilities. In this way the data on distances were collected from the routing service available by Google© Maps. This tool allowed searching over 2000 different routes considering the shortest road between the entities.

The production and operation costs have been defined proportionally based on production capacity of factories and throughput capacity of warehouses, respectively.

In terms of transportation and distribution costs, the bulk of inputs to the manufacturing plants consists of six raw materials (e.g. synthetic rubber, natural rubber, carbon black, steel, nylon and sulfur) and is provided by six major suppliers.

7.2 Definition and Characterization of Products

Currently, the Tire Company is responsible for producing and distributing over 200 products. In this application 168 different kinds of tires produced at two plants (factories) and transported via warehouses (distribution centers) are considered. The set of products is divided into four categories, as shown in Table 6 and described below.

Table 6 - Set of products in the domestic market

Tire Categories	Automobiles and Light Trucks	Buses and Trucks	Motorcycles	Agricultural and OTR	Total
Quantity	29	53	37	49	168

Source: elaborated by author

- Automobiles and light trucks: top performance tires for a wide range of cars and driving styles. Tires of 4x4 vehicles, light trucks, SUVs and cargo vans;
- Buses and Trucks: cross-ply or radial tires for trucks and buses. Designed to meet the most demanding service requirements;
- Motorcycles: tires for urban use, for motorcyclists running for long periods and for training and non-professional races under the most adverse conditions: trails, dirt tracks, mud, sand and others;
- Agricultural and OTR: tires for agricultural use combined provide the best response to farming needs. OTR (Off-The-Road) tires for road machinery and earthmovers.

In this sense, the main 168 types of tires commercialized in the domestic market were selected for the logistic system configuration of the firm. Decision makers defined the set of products considering the capabilities and settings of plants.

7.3 Preliminary Study Demands

The annual domestic demand for tires is basically defined by the vehicle production information and by the tire sales information in the retail and wholesale stores. The data are collected from the reports and estimated sales of the main Brazilians organizations and associations vehicles industry (eg. ABRACICLO, ANFAVEA) and considering the numbers of vehicles in each city or region.

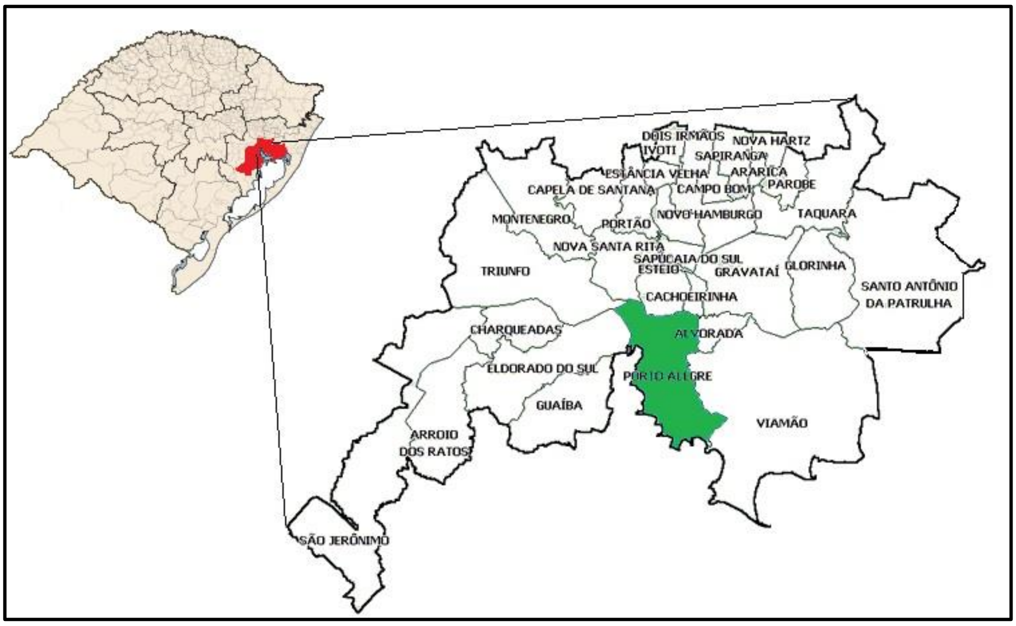
Thus, the domestic market has been divided into two categories:

- Retail Market: composition of retail stores selling different types of tires for replacement of worn-out tires;

- Industry Market: composed by the demands of domestic vehicle manufacturers.

In order to prioritize the most economically viable markets, customer zones have been established to incorporate the demand of neighboring towns around a high-demand city. As shown in Figure 20, the main city incorporates the demand of surrounding smaller cities and towns.

Figure 20 - Customer zones incorporates demands of small cities



Source: elaborated by author

In the example shown in Figure 20, the city of Porto Alegre incorporates the demands of surrounding towns. Thus, the state of Rio Grande do Sul with approximately 500 cities and towns is replaced by almost a dozen customer zones.

In addition, it was decided that only customer zones would be served wich had an annual demand exceeding 150 units. These criteria define 231 common customer zones in the retail market considering the four categories as shown in Table 7.

Table 7 - Customer zones in retail market

Categories and Markets	Automobiles and Light Trucks	Buses and Trucks	Motorcycles	Agricultural / OTR	Common Customer Zones
Retail Market	107	102	107	179	231
Industry Market	16	23	9	8	39
Total	187	125	116	125	270

Source: elaborated by author

The industry market was defined considering the main vehicle manufacturers in the domestic context for categories: market: automobiles, buses and trucks, motorcycles and agricultural. Table 7 shows that 39 vehicle manufacturers should receive tires from some warehouse.

After defining and collecting market information for each category, Table 8 summarizes the domestic demand target for the four categories in the retail and industry markets.

Table 8 - Domestic demand target of products - in thousands

Demand	Automobiles and Light Trucks	Buses and Trucks	Motorcycles	Agricultural / OTR	Amount of products
Retail Market	15,730,527	2,925,982	7,336,077	240,999	26,233,585
Industry Market	2,767,846	4,211,318	1,517,499	286,520	8,783,183

Total	18,498,373	7,137,300	8,853,576	527,519	35,016,768

Source: elaborated by author

However, the firm intends to attain a share of these demands of each segment in the retailer and manufacturer tire markets. Consequently, the customer zones demand is determine by the different market shares of each segment.

According to the marketing strategy, the firm intends to achieve 25% of the Bus and Truck category in both markets. In the Agricultural and OTR category, the market share is 20% to supply the manufacturers and 35% in the retail market. The company believes that it can a higher market share in the heavy vehicle segment. Table 9 shows the different market shares defined for each category in the retail and industry market.

Table 9 - Percentage of market share in categories

Market	Automobiles and Light Trucks	Buses and Trucks	Motorcycles	Agricultural / OTR
Retail Market	10%	25%	25%	35%
Industry Market	20%	25%	5%	20%

Source: elaborated by author

In the Motorcycle category, the company plans to maintain a conservative position in the manufactories market. However, the firm intends to achieve 25% in the retail market because it believes that their product has a competitive advantage in this category. As shown in Table 9, in the Automobiles and Light Trucks category the company plans to reach 10% in the retail market and 20% in the manufacturers market.

According to the previous market shares definitions, Table 10 presents the demands in the retail and manufacturers market considering all categories of tires produced by company. We use this information to estimate the demand of each 168 products in each customer zone.

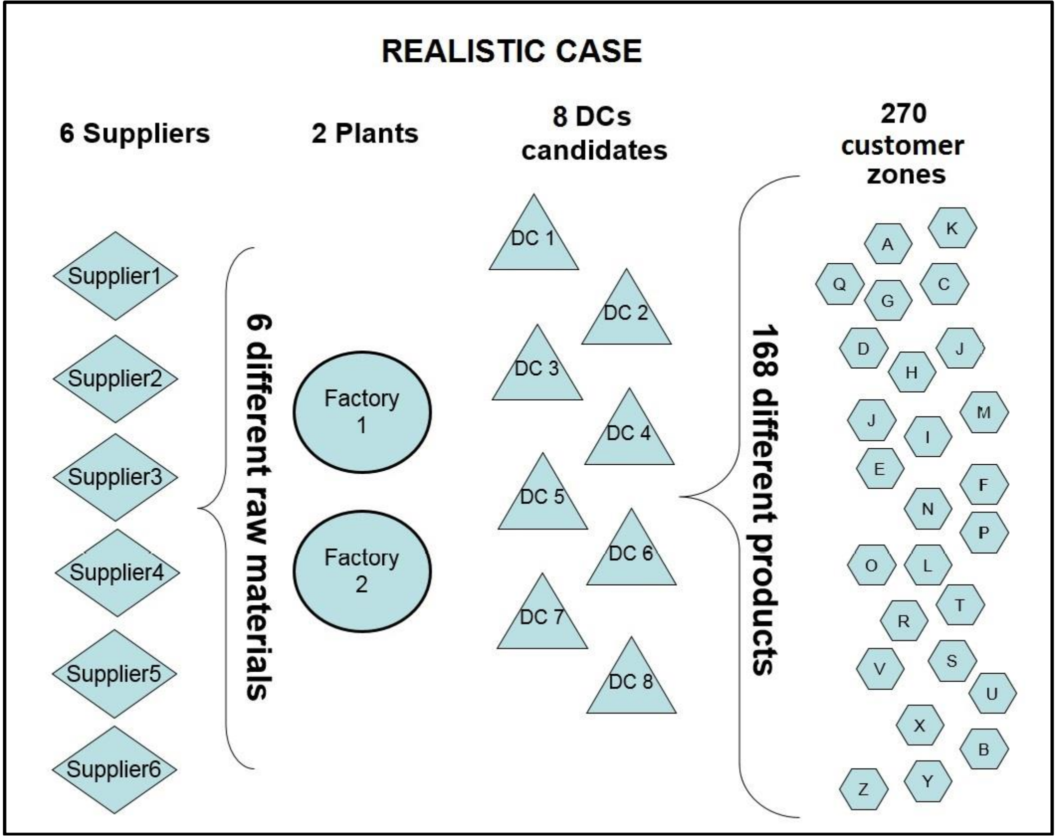
Table 10 - Market share of products

Market Share	Automobiles and Light Trucks	Bus and Truck	Motorcycles	Agricultural / OTR	Amount of Products
Retail Market	1,571,568	728,697	1,832,092	79,768	4,212,325
Industry Market	553,320	1,052,209	75,702	57,085	1,738,316
Total	2,124,888	1,780,906	1,907,794	137,053	5,950,641

Source: elaborated by author

After this intense study to collect, define and estimate the real data from a study case, the problem is structured as shown in Figure 21. In terms of transportation and distribution costs structure, the data collected and estimated express a real context faced by the company in its expansion process. Similarly, the studies performed to estimate demands to represent the real market dimensions imposed in the company's competitive environment.

Figure 21 - Realistic case problem



Source: elaborated by author

As summarized in Figure 21, the problem presents a four-echelon network: suppliers, factories, distribution centers and customers. As previously discussed, we consider 6 major raw materials from 6 different suppliers. The Tire Company already has 2 factories operating in different locations. In order to determine an efficient Supply Chain Network Design the company has 8 potential warehouses at its disposal. In addition, the demand points consist of 270 customer zones considering 231 retail customers and 39 manufacturer customers in the domestic market. The challenge is to determine a set of warehouses and commodity flows to minimize the production and transportation costs considering the full customer zones demands for 168 different products.

7.4 Realistic Case Results

According to the process adopted in the experimental procedures section in Chapter 6 previously described, the first step in the LP Rounding is to find the Lower Bound the of the Linear Programming and the set of distribution centers and plants for the lowest LP-gap. Thus, 8 runs were performed to find the set of DCs with a better LP Rounding solution. We test each run using different Upper Bounds for DC variable (e.g., in the first run the upper bound for the DC variable was 8, in the second run the upper bound for the DC variable was 7, and so on).

In order to obtain adequate solutions in LP Rounding stage, we established perturbation parameters according to the experimental tests. In the initial solution for each iteration 1 plant and 2 warehouses from the initial solutions were disabled. The percentage of arcs disabled in the initial solution was 25%.

As shown in Table 11, each run allows identifying different LP Rounding solution with different sets of distributions centers.

Column 2 shows the CPU time, clearly demonstrating the good computational performance of the LP Rounding procedure. Column 3 presents the number of DCs available for network design. The number of plants does not change because each factory is responsible for producing different types of tires, so both factories should be in operation. The Lower Bound is shown in column 5 and the LP Rounding is shown in column 6 for each run. Column 7 illustrates which DCs should be open and column 8 the respective LP-gap.

Table 11 - LP Rounding performance in the realistic case application

Run #	CPU Time	DC's	Plants	Optimal Solution	LP Rounding Solution	Selected DC's	LP-gap
Run 1	80 sec	8	2	5,95367E+08	5,95457E+08	0,1,2,3,4,5,6,7	0.0152%
Run 2	48 sec	7	2	5,95367E+08	5,95442E+08	0,1,2,3,4,5,6	0.,0127%
Run 3	28 sec	6	2	5,95367E+08	5,95427E+08	0,1,2,3,4,5	0.0102%
Run 4	28 sec	5	2	5,95367E+08	5,95436E+08	0,1,2,3,4	0.0116%
Run 5	31 sec	4	2	5,95367E+08	5,95442E+08	0,1,2,3	0.0127%
Run 6	26 sec	3	2	5,95367E+08	5,95436E+08	0,1,3	0.0116%
Run 7	21 sec	2	2	Infeasible	-	-	-
Run 8	12 sec	1	2	Infeasible	-	-	-

Source: elaborated by author

Although most runs have shown good solutions and LP-gap less than 0.02%, two runs presented infeasible solutions when the number of DC candidates was limited to 1 and 2 location facilities. In this case, the infeasible solutions happen due to throughput capacity constraints of DCs.

Run 3 obtained the best LP Rounding selecting 6 out of 8 distribution centers. In this LP Rounding solution, the LP-gap is 0.0102%. This low LP-gap evidences the excellent performance of the LP Rounding heuristic implemented. Thus, we selected this LP Rounding solution as the initial solution for Local Search implementation.

The Local Search procedure with exchange strategy using the Tabu Search technique approach is applied considering the parameters setting defined in the experimental tests. The initial solution of LP Rounding was exposed for 7.200 seconds to DCs exchange procedure.

As the experimental tests had already shown, when applied to the realistic case of the Tire Company, the Local Search improved the best result obtained by the LP Rounding procedure. The Local Search overcame the result presented in the Construction Phase, although the LP-gap had been small in the solution found in the construction phase. The LS-gap was 0.00969% in the Local Search Phase as demonstrated in Table 12.

Table 12 - Summary heuristic results in the realistic case application

	Optimal Solution	LP Rounding	Local Search
Objective Function	5,95367E+08	5,95427E+08	5,95424E+08
Min GAP	-	0.01016%	0.00969%

Source: elaborated by author

In order to evaluate Local Search performance, Table 13 shows the comparative analysis of results obtained in the LP Rounding and in the Local Search improvement procedure.

Table 13 - Comparative Performance - LP Rounding x LS Search

Distribution Center #	LP Rounding			Local Search		
	Customer Zones Assignment	Amount of Products	Rate Capacity DC	Customer Zones Assignment	Amount of Products	Rate Capacity DC
DC 1	15	664,561	22.2%	15	610,738	20.4%
DC 2	16	474,217	15.8%	16	528,606	17.6%
DC 3	24	412,006	13.7%	24	412,006	13.7%
DC 4	59	2,897,436	96.6%	59	2,896,870	96.6%
DC 5	130	1,011,253	33.7%	130	1,011,253	33.7%
DC 6	26	491,168	16.4%	26	491,168	16.4%
Total	**270**	**5,950,641**	**-**	**270**	**5,950.641**	**-**

Source: elaborated by author

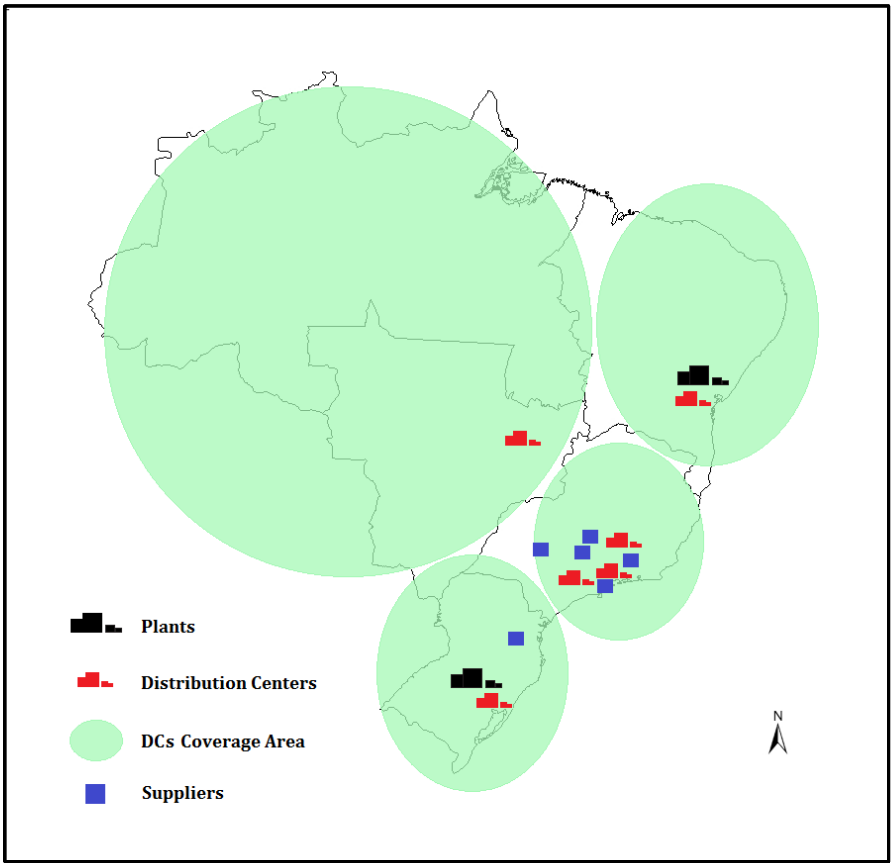
As show in columns 2 and 5, the number of customers assigned to each DC remains unchanged. In fact, this is because the Exchange strategy adopted in Local Search replaces one customer by another one assigned to a different DC. However, it is clear that the number of products assigned to each DC is altered as demonstrated in columns 3 and 6. Thus, it is possible to identify the effectiveness of the Local Search implemented using the Tabu Search techniques on the reassignment of the DCs trying to improve the initial solution obtained from the LP Rounding procedure.

In order to present the DC load ratio, the rate capacity shown in columns 4 and 7, this rate measures the occupation of each DC according to the solution presented. Note that the capabilities rates have changed as the amount of products also changed.

According to Table 13, DC 4 is responsible for 48.7% of customer zones demand (2,896,870 products) and maintains its operating capacity at 96.6% occupancy. Similarly, DC 1 and 5 show a capacity rate of 20.4% and 33.7%, respectively. In turn, DC 2, 3 and 6 show a capacity rate between 13% and 18%, and only 24.1% (1,431,780 products) of the total demand distributed. The concentration of demand in the DC 4 is shown to be relevant, because this DC is located in the southeast region, which concentrates large demands and several automobile and truck manufacturers.

Figure 22 shows a decentralized supply chain network that considers opening the DCs in different regions. In fact, the plant locations and the high transportation costs can be the reason for a decentralized logistical design. In the realistic context studied, the plants are located in the southern and northeastern regions. These plants are responsible for producing different types of tires. Therefore, it is necessary to supply all customer zones from both plants and long distances have to be covered. Furthermore, this application in this domestic context considers an SCND of continental dimensions and large distances between entities, which in turn cause high transport costs due to choice of road transportation modal. Thus, it seems recommendable to maintain regional DCs with low installation and operating costs to reduce transportation costs.

Figure 22 - Distribution Centers locations



Source: elaborated by author

In term of raw materials suppliers, the selection of suppliers to fulfill demand has an important impact on the supply chain configuration of the Tires Company. As defined previously, the company listed the 6 main raw materials, which represent the major supply costs. In this case, each supplier is located in different cities and has to provide the amount of raw material to satisfy the demand of the plants according to the utilization rate of each raw material.

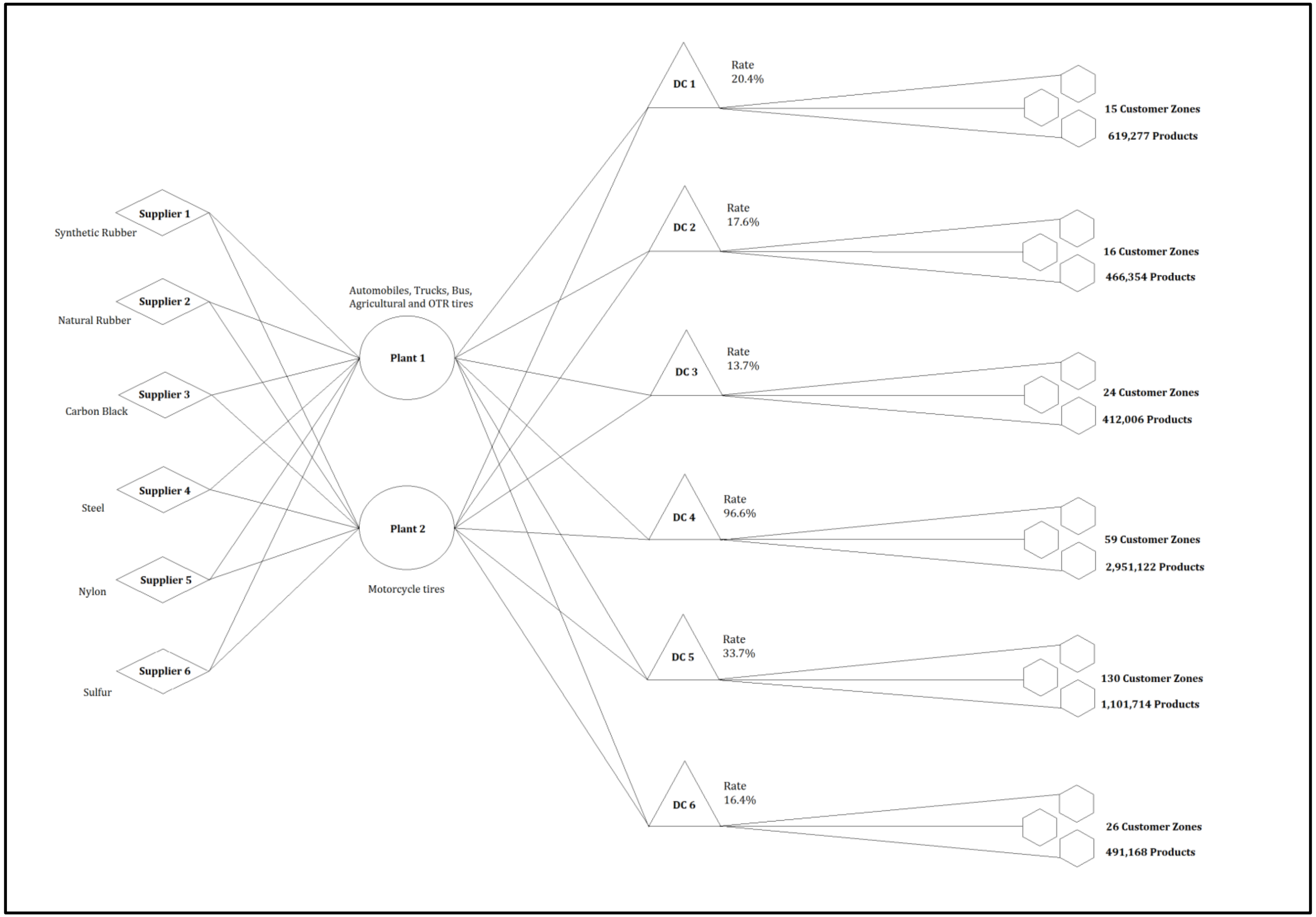
The raw materials considered in the realistic application were: synthetic rubber, natural rubber, carbon black, steel, nylon and sulfur. According to the previous definitions by the company, the suppliers deliver a raw material if, and only if, they are selected for this raw material. Thus, the supplier locations had already been defined and the challenge was to define the flow of raw material to plants at minimal transport costs.

To summarize the solution of the Tire Company problem, the Figure 23 shown a four-echelon supply chain design of the realistic case solved by the heuristic approach developed in this thesis. Figure 23 shows a representation of optimum material flow from suppliers to plants for six different raw materials and optimum location and distribution of tires from 2 plants to 6 DCs. In addition, the optimum location and flow of tires through to 6 DCs to 270 customer zones considering 168 types of tires are illustrated and the amounts are described. The example discussed in this section is intended to serve as an illustration of the applicability of the model to practical sized problems and to a competitive industrial environment.

Finally, in the heuristic approach implemented we obtained interesting results. The capacities rate for each DC may contribute to decision-making in change scenarios (e.g. tax policies, economic factors, etc.). The solution time and the gaps within an acceptable limit evidence a good performance of the heuristic proposed in the real and competitive context of a multi-commodity industry.

In this chapter the heuristic approach proposed in this thesis is implemented in a realistic context of an industry responsible for producing and distributing of tires in the domestic market. Real data were collected and the different market shares were estimated to represent the real problem faced by the company. The proposed heuristic provided excellent results in both phases. In the LP Rounding and Local Search, the quality solutions are evidenced by the small percentage gap obtained in each phase. In the next chapter, we present the main conclusions and future researches that can be derived from this research.

Figure 23 - Supply Chain Network Design for Tire Company



Source: elaborated by author

8 CONCLUSION AND FUTURE RESEARCH

This thesis presents a heuristic approach to deterministic Supply Chain Network Design considering a multi-commodity four-echelon logistics system. The main objective was to implement a heuristic solution method based on Operations Research to minimize the total cost in the supply chain network.

In order to present the major conclusions, we summarized the specific objectives of this thesis and point out important contributions regarding this intense research work.

Regarding comprehensive literature research, though the body of literature on Supply Chain Network Design problems is extensive, we reviewed the most relevant and recent literature within the context of mathematical modeling problems. Relevant authors and seminal papers involved in mathematical modeling research for network design were examined and the main contributions were summarized in the literature review chapter.

We dedicated separate sections to present an overview of general concepts of supply chain and deterministic mathematical modeling researches. In first section, we discuss the major aspects and concepts of supply chain and logistics operations, especially decision and mathematical modeling at the strategic, tactical and operational levels.

In the other sections, we listed deterministic mathematical formulations that conducted the modeling and heuristic approach developed in this thesis. In this context of research major authors and seminal papers supported the development of the formulation and mathematical modeling proposed in this study. (GEOFFRION; GRAVES, 1974; JAYARAMAN; PIRKUL, 2001; LEE; DONG, 2008; LEE; KWON, 2010).

Moreover, this literature review highlighted the important role of facility location in the competitive business environment. This role is becoming more important with the increasing need for complex models that capture many aspects relevant to real-life problems.

In order to present mathematical modeling and formulation, we consider a supply chain network composed of four layers: suppliers, plants (factories), distribution centers (warehouses) and customer zones (clients). The main objective in this formulation is to minimize the total fixed and variable cost associated with a flow of raw materials and products in the supply chain network considering the multi-commodity and single-period aspects. We formulated the Supply Chain Network Design problem using the Mixed Integer Linear Programming inspired by Jayaraman and Pirkul (2001). Important aspects were decisive for an adequate and compliant mathematical formulation (e.g., integer decision variables definition, cost structures, flow constraint equations, etc.). From a modeling point of view, the proposed model efficiently represented the problem under study and can be extended to a multi-modal supply chain model and to a multi-period model.

The heuristics approach to problem solving was developed in two major phases: Construction phase and Local Search phase. In the Construction phase an LP Rounding procedure is designed. The linear programming based rounding heuristic was developed to find an initial solution for a set of instances. As mentioned before, we randomly generated experimental instances to capture realistic characteristics as the instances researched in the literature review. In addition, the experimental instances consider medium and large sizes associated with four-echelon network.

The main contribution of the proposed LP Rounding heuristic approach is the perturbation procedure based on a multi-start strategy. In the perturbation step, the multi-start strategy enables the LP Rounding procedure to deliver different high quality solutions from each new iteration. In the multi-start procedure, a number of plants, warehouses and a certain percentage of assignments (customers to warehouses) are disabled in the previous solution before starting a new iteration. This multi-start strategy ensures that different solution spaces are explored and that good solutions are found for each iteration. The numerical results shown LP-gaps ranging between 0.374% and 4.178% and the average LP-gap of 2.19% in the best solutions, considering the 25 experimental instances.

These results show the efficiency of the approach using an LP Rounding heuristic with a multi-start strategy.

In the Local Search phase an exchange strategy is conducted based on Tabu Search techniques. In this phase, the best LP Rounding solution found in the Construction Phase was adopted as the initial solution. At first, the Local Search is conducted at customer level by randomly exchanging two customers assigned to different warehouses from the initial solution. However, to avoid visiting the same neighbor space, the Tabu Search is applied. In this sense, a short-term memory Tabu Search algorithm was implemented considering parameter setting according to the preliminary experimental tests. Numerical experiments indicate that the Tabu Search generates satisfactory results in terms of solution quality.

In the Local Search, the numerical results show that the new procedure performs well and can achieve solutions within less than 1% of the linear relaxation bound in the established computational times. Considering very large instances, the effectiveness of the heuristic approach implemented is demonstrated by the high quality of the best solution identified, which have a gap below 1% in 7 out of 25 instances (28%). In addition, in more than half of the instances (13 out of 25) the best solution deviates less than 1.75% from optimal solution. As mentioned, a large scale test instance was solved and the results demonstrate the practicality of the mixed integer linear programming model and the solution algorithm proposed in our heuristic approach.

In the computational implementation of the solution method, we proposed a Mixed Integer Linear Programming formulation based on a literature review. In order to overcome the computational difficulties when solving large size instances, the formulations and algorithm have been implemented in C++ code language using the optimization engine COIN-OR.

In order to solve problems in similar dimensions to those found in the literature review, 25 experimental instances were generated for the computational experiments. The experimental instances represent the supply chains in four operating levels: supplier, plant, DCs and customers. All experimental instances represent very large supply chains with more than 150 customer zones. Many of the instances have more than one hundred product and involve dozens of potential distribution centers. Moreover, the experimental instances capture quality from real supply chain problems (e.g., operational fixed cost, production and transportation costs, raw material utilization rate, large demands for products, etc.). Considering the experimental tests shown in Chapter 6, the heuristic approach proposed obtained an average gap less than the average gap of literature review (1.96% versus 3.306%).

In the last chapter, a practical application based on a tire manufacturer was studied in order to validate both the applicability and adequacy of the mathematical modeling to real world problems. We seek to expand the contribution of this research in the practical application to a realistic enterprise context. In addition, application of mathematical models in practical scenarios improves the supply chain design modeling researches (VISENTINI; BORENSTEIN , 2014).

In a brief description of the problem, the company desires to redesign its logistics project integrating four layers in the supply chain network operation. The problem consists in selecting the suppliers of main raw materials, determining the production flow in each plant, and which candidate distribution centers should be opened.

The realistic problem under study considered a set of 6 major raw materials from 6 different suppliers. The plant locations are already known and the company has 8 potential distribution centers at its disposal in different locations. In addition, the demand points consists of 270 customer zones (231 retail and 39 manufacturers). Lastly, the objective was to determine a set of warehouses and flow of tires to satisfy all customer zone demands for 168 different products.

One of the main difficulties for application in real cases is the availability of data to adequately structure the network problems in the supply chain (LEE; KWON, 2010). To overcome the absence of data, we conducted an intense survey to collect the informations (e.g. transportation and operations costs, capacities of plants and distribution centers, demands for each product, market shares, etc.) to structure the real context of the problem faced by the company in this case study.

After the preliminary steps, the heuristic approach was applied in two phases. In the Construction phase, the LP Rounding procedure was conducted to 8 different scenarios. The best lower bound was found selecting 5 out of 8 distribution centers. In the LP Rounding procedure solution the LP-gap was 0.01016% from the LB solution. In the Local Search phase, the best LP Rounding solution was adopted as the initial solution. Through the exchange strategy based on the Tabu Search techniques the solutions were extremely satisfactory. The Local Search method improved the best LP solution and the new gap found was 0.00969%. Considering the good solution gap, this result provided an adequate solution to the problem presented in the real application case studied. In terms of network configuration, the heuristic solution proposes a decentralized network configuration for a realistic case studied. A reasonable response to DC decentralization can be considered as due to the high transport costs associated with road transport mode. We can emphasize that in a realistic application case the LB solutions were lower than the LB solution in the computational implementation tests, probably due to the variability of costs involved in the real context.

Lastly, the results suggest that the heuristic approach proposed is able to solve realistically sized problems within an acceptable computational time. The mathematical modeling developed in this thesis captures key features relevant to efficient Supply Chain Network Design and provides a satisfactory performance in problems presenting a considerable degree of detail and complexity. The degradation of the objective function is generally less than 2%. However, for the most difficult instances, we observe a significant optimality gap of about 3%.

Considering the relevant contributions of the heuristic approach developed in this study for Supply Chain Network Design problems, we believe that future studies could include the follow:

(i) extension of the models considering the demands for multicommodity over a multi-period horizon;

(ii) integration of strategic inventory decisions and stochastic data (e.g. demand uncertainty);

(iii) extension of the SCND modelling considering multimodal aspects for transportation costs;

(iv) incorporation of the global strategic decisions (e.g. transfer prices, etc., and;

(v) extension of the proposed heuristic optimization procedure to different industries and different supply chains.

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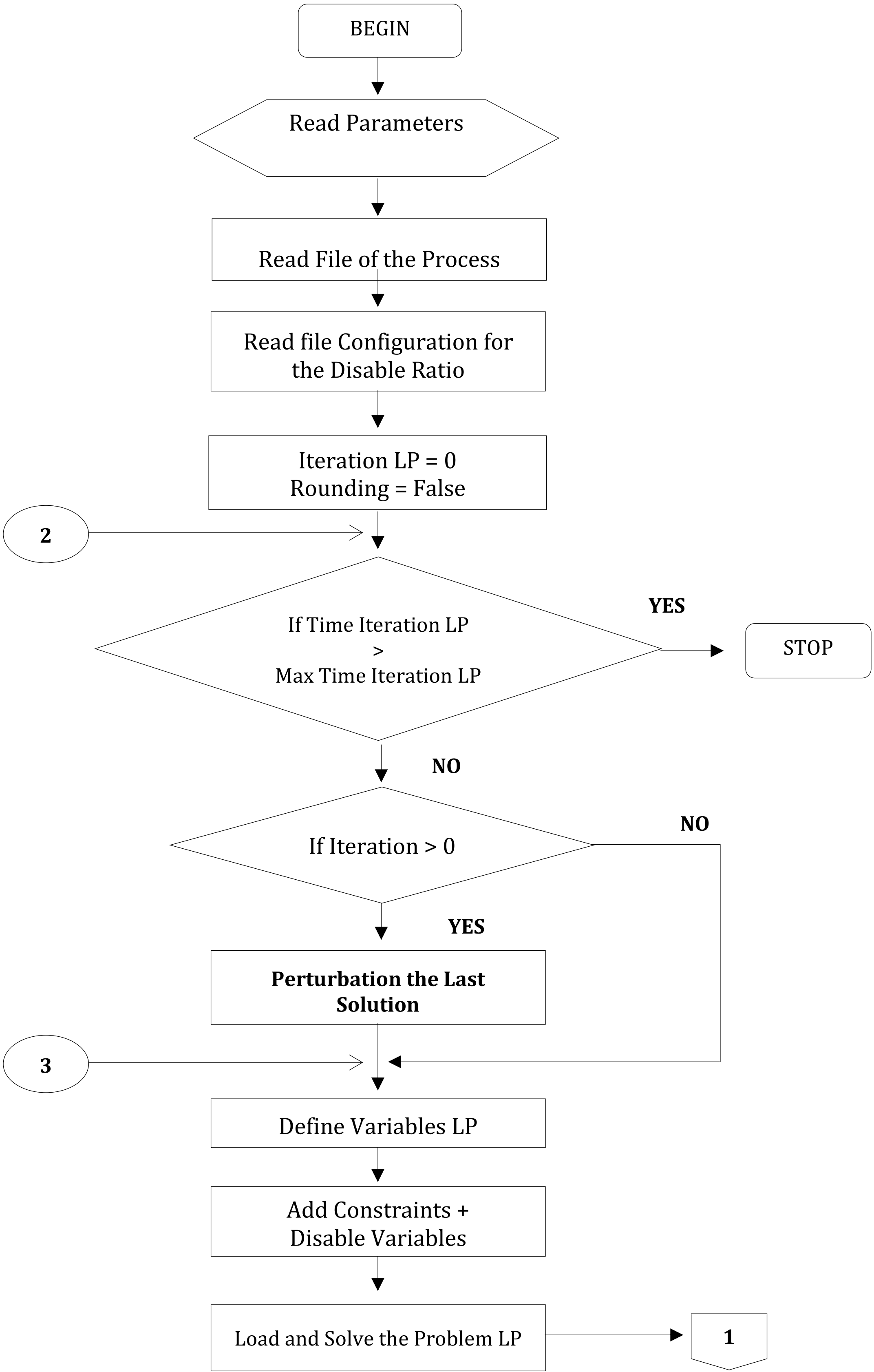
Appendix A

A1: Main scheme of the LP Rounding Heuristic



Main Scheme of the Heuristic (cont.)

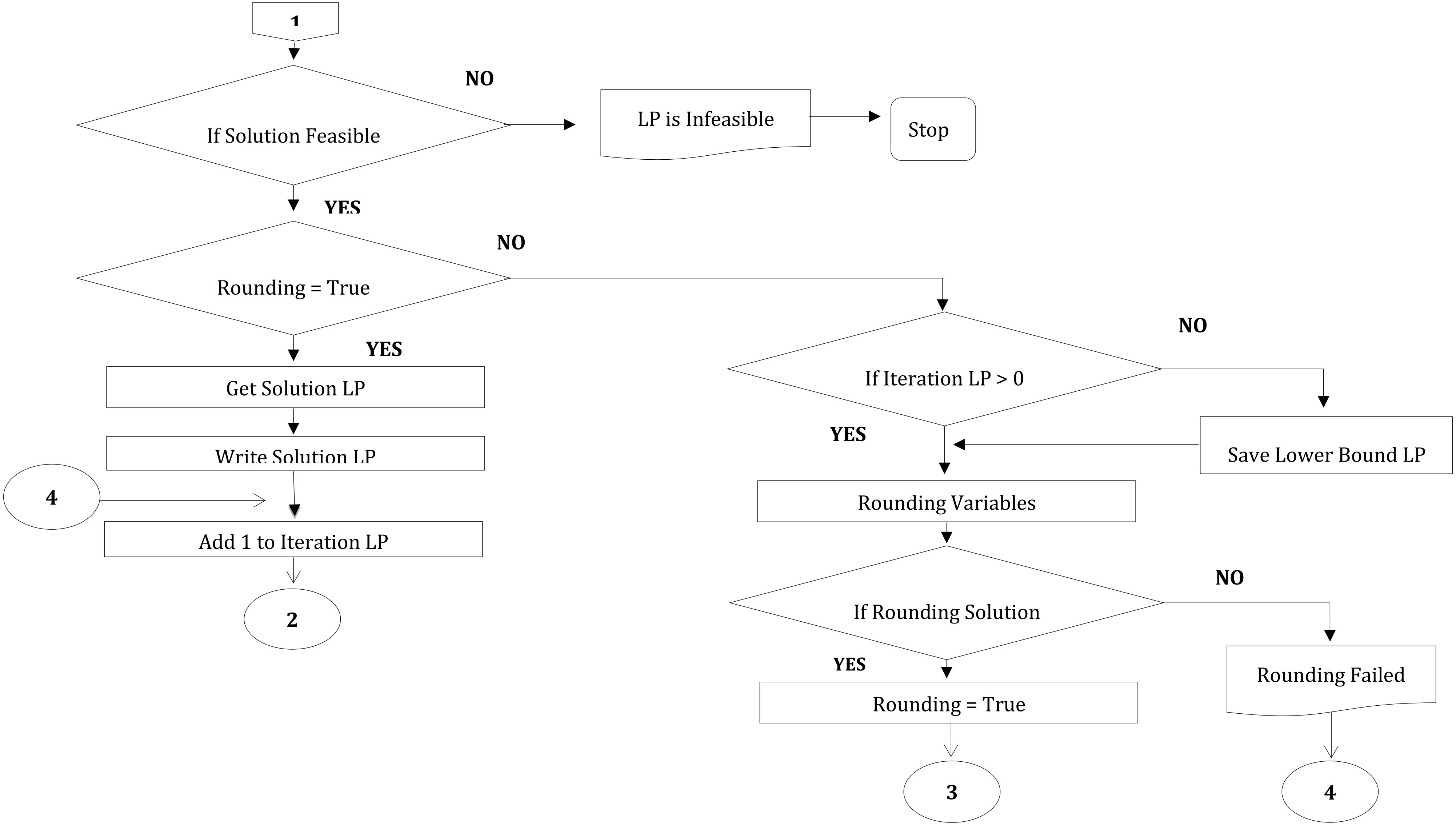


Table 14 - Detailed results of rounding heuristic application

									ROUNDING PROCEDURE								
									Solutions of 200 iterations			Top 50 Solutions		Best Solutions Rounding			
Inst #	Supplier	Raw	Plant	DC	Product	Customer	Quantity of Products	Lower Bound (OF)	Feasible Solutions	Average UB (OF)	Average LP gap	Average UB (OF)	Average LP gap	Upper Bound (OF)	LP gap	Plants Selected	DC's Selected
Inst1	5	5	3	10	5	150	1,000,000	16,592,352	158	19,431,432	17.11%	18.876.248	13.76%	17,215,800	3.76%	2	7
Inst2	5	5	3	20	5	150	1,000,000	16,101,237	166	18,956,568	17.73%	18.417.266	14.38%	16,718,500	3.83%	3	9
Inst3	5	5	3	30	5	150	1,000,000	15,018,493	179	17,278,698	15.05%	15.959.786	6.27%	15,317,400	1.99%	3	9
Inst4	5	5	3	40	5	150	1,072,388	19,048,268	155	21,196,235	11.28%	20.224.846	6.18%	19,615,710	2.98%	3	6
Inst5	5	5	3	50	5	150	1,000,000	16,882,783	156	18,585,113	10.08%	18.121.630	7.34%	17,081,200	1.18%	3	8
Inst6	5	5	3	10	10	150	1,575,000	30,235,854	149	32,492,792	7.46%	32.149.010	6.33%	31,499,000	4.18%	3	7
Inst7	5	5	3	10	40	150	750,982	12,785,532	112	13,243,646	3.58%	13.235.569	3.52%	13,176,877	3.06%	3	4
Inst8	5	5	3	10	100	150	1,583,100	28,715,588	144	31,357,099	9.20%	30.620.942	6.64%	29,228,562	1.79%	3	7
Inst9	5	5	3	20	10	150	1,237,500	25,691,500	121	27,111,688	5.53%	26.696.888	3.91%	25,807,550	0.45%	3	9
Inst10	5	5	3	30	10	150	1,575,000	27,442,279	127	30,480,642	11.07%	29.939.970	9.10%	27,992,000	2.00%	3	12
Inst11	5	5	3	40	10	150	1,575,000	30,697,742	119	32,514,663	5.92%	31.845.294	3.74%	31,007,400	1.01%	3	15
Inst12	5	5	3	50	10	150	1,575,000	19,707,714	114	21,177,272	7.46%	20.801.270	5.55%	19,781,500	0.37%	3	12
Inst13	5	5	3	20	10	150	3,000,600	61,288,232	177	63,148,294	3.03%	63.061.134	2.89%	62,675,404	2.26%	3	10
Inst14	5	5	3	20	50	150	3,152,400	60,023,774	164	63,712,455	6.15%	63.518.219	5.82%	61,865,024	3.07%	3	17
Inst15	10	10	5	10	40	150	1,576,200	14,048,397	131	14,418,855	2.64%	14.303.812	1.82%	14,261,230	1.51%	4	3
Inst16	10	10	5	10	150	250	1,552,062	34,777,168	134	36,532,736	5.05%	35.614.207	2.41%	35,183,008	1.17%	4	6
Inst17	10	10	5	20	150	250	1,552,062	34,497,123	188	37,401,134	8.42%	37.124.430	7.62%	35,864,296	3.96%	5	12
Inst18	10	10	5	10	5	150	1,509,505	17,832,191	154	20,447,256	14.66%	19.535.666	9.55%	18,393,100	3.15%	5	6
Inst19	5	5	3	5	150	250	1,509,505	31,716,253	105	33,421,644	5.38%	32.996.230	4.04%	32,952,820	3.90%	3	3
Inst20	25	25	20	15	20	270	1,351,892	37,488,563	167	39,550,879	5.50%	38.914.612	3.80%	38,599,067	2.96%	12	5
Inst21	20	20	20	10	15	200	750,128	20,129,200	157	21,088,021	4.76%	20.549.598	2.09%	20,226,074	0.48%	19	4
Inst22	15	15	10	5	10	150	374,556	8,685,207	184	10,146,071	16.82%	8.809.644	1.43%	8,762,447	0.89%	7	2
Inst23	20	20	5	5	170	300	4,879,009	124,587,459	199	125,641,382	0.85%	125.605.739	0.82%	125,490,467	0.72%	5	5

Inst24	5	3	1	5	3	250	5,611,652	86,783,653	200	89,197,129	2.78%	88.716.570	2.23%	88,617,430	2.11%	1	2
Inst25	5	5	3	30	5	100	680,000	11,922,894	133	13,079,878	9.70%	12.192.886	2.26%	12,146,100	1.87%	3	5
*** OF = Objective Function**										**Average**	**8,29%**	**Average**	**5.34%**	**Average**	**2.19%**		