Tesis Doctoral

Planning Logistics in Healthcare Networks: Analysis and Resolution

"Planificación de la Logística en Redes de Salud: Análisis y Resolución"

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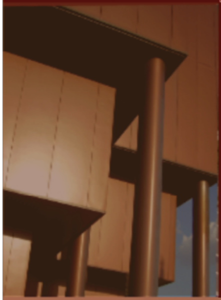

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Tesis Doctoral
Organización Industrial y Gestión de Empresas

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

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A mis padres, Juan y Bárbara, que me inculcaron el valor del esfuerzo y el tesón, y a quienes debo todo lo que soy.

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Resumen

Las Redes de Salud se basan en el trabajo en común de una variedad de entidades públicas y privadas (hospitales, unidades de servicios específicos, profesionales sanitarios,...) a nivel local o regional, en busca de una gestión efectiva, con toma de decisiones y coordinación eficientes. Esta tesis analiza la siguiente pregunta de investigación: "¿Cómo pueden las organizaciones integrar su red logística interna" Las teorías, conceptos y directrices de integración de la Cadena de Suministro se han aplicado para investigar este problema.

En redes de salud ya funcionando, la aplicación de procedimientos de planificación centralizada se identifica como la estrategia de gestión más adecuada para racionalizar y pilotar los procesos de cambio. Por ello, planteamos abordar el objeto de la tesis mediante un modelo de programación lineal entera mixta (MILP) de nivel táctico, del que emanarán las decisiones sobre la visión global del diseño de la red y la política de coordinación entre los miembros de la red. Además de la adopción de herramientas de optimización para proporcionar un marco para operaciones eficientes en costes, hemos identificado como aspectos clave en la consecución efectiva de la integración logística en este tipo de redes el intercambio de información y el cumplimiento de acuerdos de nivel de servicio.

Como caso práctico, hemos realizado esta integración en la Red Andaluza Regional de Laboratorios Clínicos (ANCL), una red sanitaria extensa con hospitales, clínicas y laboratorios clínicos dispersos geográficamente, que inició una estrategia de cambio organizacional para mejorar la accesibilidad al servicio de pruebas clínicas, la calidad del servicio y propiciar ahorro de costes. Sobre el MILP que resulta al abordar este caso de estudio, hemos aplicado diferentes estrategias de solución. Puesto que este modelo de optimización ha de usarse como el corazón de un Sistema de Soporte a la Decisión (DSS) a disposición de los planificadores ANCL

para realizar análisis de escenarios, la agilidad en la generación de soluciones es un requisito primordial. Basándonos en nuestra experiencia con la ANCL, parece que tanto la integración de los sistemas de Tecnologías de Información de los diferentes miembros en la red como la centralización del procedimiento de planificación logística (a través del cual se fijan las directrices de coordinación anual) son de inestimable ayuda para la alineación del modelo operativo y el comportamiento organizacional en torno a demanda, capacidad y configuración de red. Esto sugiere que aunque tales proyectos de integración sean difíciles, costosos y complejos, el esfuerzo parece valer la pena.

Abstract

Healthcare networks bring together a wide range of public and private entities (hospitals, specific service units, healthcare professionals, …) at local or regional level that seek for management effectiveness, decisional efficacy and coordination. This thesis analyzes the problem statement: "How can those organizations integrate their internal logistic network?" Theories, concepts and integration guidelines from supply chain management theory have been applied to investigate this problem.

On healthcare networks already in place, the application of centralized planning procedures is the more appropriate management strategy to rationalize and pilot the change processes. Hence, a general tactical level model is stated as a mixed integer linear programming (MILP) model supporting decisions on the global view of network layout and the coordinating policy among facilities in such networks. Apart from the adoption of optimization tools to provide a framework for cost-efficient operations, we have identified that information sharing and service level agreements are the key aspects in the effective accomplishment of logistics integration.

We have conducted a case study at the Andalusian Regional Network of Clinical Laboratories (ANCL), a large healthcare network with geographically dispersed hospitals, clinics, and testing laboratories, that initiated an organizational strategy to enhance accessibility to services, quality of care and cost savings. Different solution strategies have been addressed in the MILP model that arises, in order to embed this model into a graphical, interactive and responsive Decision Support System (DSS) tool to support ANCL planners' analysis of What-If scenarios. Drawing on the ANCL case study, it appears that the integration of the Information Tecnologies (IT) Systems at the different facilities and locations within the network and the centralization of the logistic planning procedure can be of invaluable help

for aligning operational models and organizational behavior around demand, capacity and network configuration. This suggests that although such integration projects are difficult, costly and complex, they seem worth undertaking.

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Notation

3PL	Third-Party Logistics partner
AC	Autonomous Communities
AGA	Average Geographical Accessibility indicator (a QoS measure in the ANCL's delivery service)
AHA	Andalusian Health Administration, wider than SAS
AMPL	A Mathematical Programming Language
ANCL	Andalusian Network of Clinical Laboratories
AUD	All-units discount
API	Application Programming Interface
BD	Bender Decomposition
CBD	Classical Bender Decomposition
CC-MCNFP	Capacitated MCNFP with concave costs
CORAL	Applied Project for the effective integration among the public hospitals in the ANCL, around interoperability and tactical logistic planning.
DCC	Dissaggregated Convex Combination Method for Linearization of PWL functions
DSS	Decision Support System
DTP	Demand Transfer Point
ESB	Enterprise Service Bus
GUI	Graphical User Interface
GBD	Generalized Bender Decomposition

ILS	Information Laboratory System
INSALUD	“Instituto Nacional de Salud”
HIP	Healthcare Integration Platform
IT	InformationTecnologies
LTL	Less-than-truckload
LogDCC	Logarithmic Dissaggregated Convex Combination Method for Linearization of PWL functions
LP	Linear programming
MAUD	Modified all-units discount
MC	Multiple Choice Method for Linearization of PWL functions
MFS	Maximum Feasibility Subsystem
MIBLP	Mixed-integer bilinear programming problem
MILP	Mixed integer linear programming
MINLP	Mixed-integer non-linear programming problem
NFP	Network Flow Planning
NP-hard	Non solvable in Polinomial time hard problem
PHP	PHP: Hypertext Preprocessor
POE	Point of Extraction
PWL	Piecewise Linear function
QoS	Quality of Service
RMP	Relaxed Master Problem
SAS	“Servicio Andaluz de Salud”
SC	Serving Center
SC	Supply Chain
SCM	Supply Chain Management
SOA	Service Oriented Architecture
SP	Primal problem, sometimes just Subproblem

1. INTRODUCTION

> *Estimates for the cost of logistics related activities generally range from around 30-40% of overall healthcare costs, second only to labor expenses as a priority for healthcare cost containment.*
>
> *- (Nachtmann&Pohl, 2009) -*

In the vast majority of countries, the healthcare sector is the focus of a great deal of attention from public decision makers and media alike. Although healthcare is by definition a clinically driven environment, the practice of patient care is supported by a range of activities that notably include purchasing, inventory management, and the distribution of supplies to the point of care. These activities are associated with healthcare supply chain management, also referred to as healthcare logistics (Landry & Beaulieu, 2013). Improving the efficiency of such logistics can provide opportunities for healthcare institutions and health systems to increase the quality of care and reduce costs.

1.1 Background and Motivations

In recent years the ever-increasing cost containment is stressing more and more the delivery of health services. This process started in Europe by the nineties in the last century, when authorities established new regulatory frameworks to ensure both access to high-quality care for the whole population and containment of healthcare costs. New budget-constrained activity-based financing systems were set up, with the argument that it was possible to reduce costs and increase quality simultaneously through efficiency gains.

In Spain, the focus of the reform started in the 90's shifted towards changes in the financing, organizational and management practices. The cost containment priority has been pursued together with a decentralization process that has transferred the responsibility of managing health services from the INSALUD (the social security agency formerly responsible for the financing and delivery of health services) to the Spanish Regional Governments (Autonomous Communities, ACs from now on). The 17 ACs have nowadays the responsibility for planning, financing, and providing healthcare services, social and community care, and public health (Sánchez-Martínez, Abellán-Perpiñán, Martínez-Pérez, & Puig-Junoy, 2006).

Nowadays, each AC addresses its own decision-making process to maintain a viable regional healthcare system. In particular, there are strategic decisions concerning to the number of hospital services, their location and details on the assigned resources (beds, doctor, nurses, etc). Tactical decisions have to be faced to ensure enhanced integration and efficiency among the organizations (private or public) that belong to the network, to help the attainment of long-term objectives while providing a framework to the everyday functioning of the organization. Ultimately, operational decisions define the healthcare services delivered which should be fair and adapted to the need of population.

Organizing in networks systems has been proved to be useful in operational terms (resource allocation, knowledge sharing) and in clinical terms (intervention practices and procedures facilitating service coordination). They can be viewed as multi-site organizations with complementary production possibilities at several locations, with different kind of relationships (varying strength of linkages between the facilities and heterogeneous IT-Structures) so that stakeholders often encounter difficulties in the management of the logistic inter-dependencies that evolve between the different facilities. Besides, healthcare supply chain activities represent a significant part of the total healthcare costs, and have a great deal of unmet potential in terms of cost savings. However, complex decision problems arise when facing the measures to rationalize and integrate the supply of health care services and enhance efficiency.

1.2 Aims and Objectives

This thesis analyzes the problem statement: "How can healthcare organizations integrate their internal logistic network?" Theories, concepts and integration guidelines from supply chain management theory have been applied to investigate this problem. These theories are best suited to analyze the integration of internal logistic networks, because the entities within such a network behave before the integration almost like independent facilities in a logistic sense.

Logistics management plays a central role in the definition of a framework to efficiently provide health services. Our research hypothesis is that a centralized planning procedure is the more appropriate management strategy to rationalize and change the target healthcare networks. Further, such decisions are addressed at the strategic and tactical levels, thereby crucial in the design of the structure of the delivered service.

Our primary objective in this thesis is the *Integrated Management to align the long-term decisions with new business perspectives, based on improved coordination and logistics.* To accomplish it, we have addressed the following secondary objectives:

- *O1: Literature Review* to identify the state of the art on models and methodologies to support this type of logistics decisions.
- *O2: Mathematical Modeling* to characterize the features that define the decision making problems, in terms of parameters, objectives, decision variables and constraints.
- *O3: Solution Strategies* to take advantage of the knowledge of models' structure to define solution methods for efficiently solving them.
- *O4: Decision Support System* to make easier the What-If Analysis to be conducted for informed decisions on extensive networks.

1.3 Scope and Delimitations

Healthcare networks bring together a wide range of public and private actors (hospitals, specific service units, healthcare professionals and managers) at local or regional level that seek for management effectiveness, decisional efficacy and coordination.

We assume healthcare networks as multi-site organizations which many often exhibit complementary production possibilities at several locations, with different kind of relationships (varying strength of linkages between the facilities and heterogeneous IT-Structures), thereby making the management of the logistics inter-dependencies between the different facilities difficult. The scope of this thesis is the improvement of logistics management in such multi-site networks.

Logistics management was defined by the Council of Supply Chain Management Professionals (CSCMP) in 2010 as follows: "Logistics management is that part of the supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services, and related information between the point-of-origin to the point-of-consumption in order to meet customers' requirements (www.cscmp.org)."

The underlying assumption is that the supply chain is yet in place. Hence, assume a network of facilities, which are of different types: some of them have a supply of certain products (known as commodities), others a demand for them. Commodities can be numerous and very different, e.g., in their mass, volume, or value. Some facilities may be able to carry inventory, usually with a commodity-dependent capacity and cost. Handling cost may result from commodities passing through a facility, such as a distribution center, regardless of whether they are moved to inventory or not. Quite commonly, inbound logistics costs can be reduced by looking for third-party logistics providers that can bring to bear lessons learned in other industries. Particularly, they allow for economies of scale: the larger a shipment, the lower the effective per unit shipping cost. Thus, the facilities are joined by transport relations, and on each transport relation, different transport tariffs are available corresponding to concurring offers of freight forwarders and available transportation modes.

1.4 Reading Guide

Once presented the introduction to the thesis research on the integration of internal logistic within healthcare networks, we outline the thesis document as follows.

Chapter 2 "Logistics Healthcare Foundations" highlights the main bodies of academic literature that serve as the starting point for approaching the problem statement analyzed in this research work.

Chapter 3 "Network-based Optimization Model" addresses a generic modeling and analysis methodology for logistical long-term decisions in extensive healthcare networks. It proposes a multicommodity capacitated network flow problem with concave routing costs, considering also outsourcing, overload and underutilization facility costs. This MILP model supports the tactical level decisions on the global view of network layout and the coordinating policy among facilities in such networks, with the aim of providing a framework for cost-efficient operations.

In chapter 4 "Solution Strategies" we face a major issue when an optimization model has to be put into operation: the solution method. Firstly, we study different alternatives to linearize the non-convex costs involved in the referred MILP model. Secondly, we take advantage of the structural properties to apply a Benders strategy to split our problem into continuous and integer parts. Both analyses have been done on the assumption of the optimization model being solved using state-of-the-art commercial solvers.

In chapter 5 we illustrate the methodological approach discussed in the earlier chapters in a case study concerning to the Andalusian Network of Clinical Laboratories (ANCL), a large healthcare network with geographically dispersed hospitals, clinics, and testing laboratories. We present the successful reengineering/ redesign experiences of the ANCL authorities in transforming the operational processes. Termed Project CORAL, the implementation of this strategy has been based on improved interoperability and logistical integration among the public hospitals in the regional health system (Contreras, 23Jun2012). Firstly, interoperability has been strongly related to the adoption of a new business perspective, built around new flows on information to track service level agreements (SLA) among members. Second, a new coordination and planning procedure has been developed to serve the purpose of defining the tactical logistics in a whole-system perspective.

In chapter 6 we summarize the contributions achieved by each of the publications appended in this thesis. As a general overview, they provide an insightful study of the practical process of integrated logistic planning in healthcare networks. Focusing in the ANCL, the developed planning procedure has been embedded in a graphical and interactive DSS tool, which has proven invaluable in helping planners to reap a better utilization of the fully-equipped labs and the reduction of outsourced tests, with major attention to customers' satisfaction.

Chapter 7 is devoted to present the global conclusions and further research lines.

Finally, we present in appendices the publications performed during the Ph.D. course. Drawing on the ANCL, the appended papers show the usefulness of defining models considering the key features of real systems, which accounting for the global view of the involved network layout, enable stakeholders to define the coordinating policy among facilities with realistic assessment of long-term operations costs.

2. HEALTHCARE LOGISTICS FOUNDATIONS

This chapter is devoted to identifying models and methods useful to support logistic planning problems in healthcare networks. Logistics has traditionally been defined as the process of planning, implementing, and controlling the efficient flow and storage of goods, services, and related information as they travel from origin to consumption points (Arshinder, Kanda, &Deshmukh, 2008).

In order to overview the context of our target problems, we again recall that healthcare networks bring together a wide range of public and private actors (hospitals, specific service units, healthcare professionals and managers) at local or regional level that seek for management effectiveness and coordination efficiency. Planning is one of the management strategies to face the task of service delivery in such complex contexts. We give a glance of the planning processes needed within healthcare systems, the different lead times (planning horizon) associated with the decisions to be made outlining the body of work on planning healthcare according to strategic, tactical and operational levels.

Once given the context, since the task of designing and operating healthcare networks belongs to the broad realm of supply chain management, we conduct a review of supply chain and logistics management models connected to our research. We confine our literature review to works explicitly dealing with logistic issues that apply mathematical optimization techniques.

Finally, we draw the main lines of real-life healthcare logistics problems. To great extent, the challenges in healthcare supply chain management turn around hospitals as the key elements in healthcare delivery networks. They implement the activities and processes, and also are on the receiving end of a wide range of supplies that support the delivery of care.

2.1. Healthcare Planning

At the strategic level, the Network Design Decisions are addressed from a whole-system perspective to provide the network design that should allow for the better service provision, setting the layout and allocation of long-lasting resources to cover necessities in a long period –i.e. location of facilities, their capacity and the assignment of the territory to be served-. The emphasis is usually on objectives such as ease of access and/or speed of access, as well as the attainment of cost-efficient service delivery. However, many often the strategic configuration goes beyond network design and customer service considerations, and the major goal is long-term follow-up and disease monitoring to decrease the risk of complications and/or death (Charfeddine, Augusto, & Montreuil, 2010; Y. Zhang, Berman, Marcotte, & Verter, 2010). Charfeddine et al. (2010) address the districting problem in a Quebec province (Canada) to the redesign of chronic diseases services distribution so as to facilitate their accessibility to the assigned center (patient driving distance) for patients residing in distant zones while, at the same time, optimizing the opening of those services at the center. In Zhang et al. (2010) a network of mammography centers in Montreal is designed aiming at reducing the frequency of life-threatening illnesses by protection and early detection, proposing a non-linear optimization problem. For a review of location problems as a critical element of strategic planning we refer to (Daskin & Dean., 2005).

Once the network is in place, the tactical level focuses on what to do in the midterm to help the organization achieve the long term objectives determined by strategic planning. As an example, the tactical resource planning referred to hospitals is often focused on elective patient admission planning and the intermediate-term allocation of resource capacities (Hulshof, Boucherie, Hans, & Hurink, 2013). In Hulshof et al. (2013) the main planning objectives are equitable access for patients, meeting production targets and/or serving the strategically agreed number of patients, while making an efficient use of resources. Another example in a wider scenario is reported in Govind et al. (2008), which copes with a network of hospitals in a predefined geographical area to determine the bed capacity that each hospital should devote to different disease classes in order to maximize speed of access to care. The presented model accounts for the spatio-temporal pattern of disease incidence in the area and the driving speeds on different types of roads in determining the speed of access. Similarly, Santibáñez, Bekiou, & Yip (2009) face the problem of the location of clinical services and allocation of bed capacity across the services at each hospital within a real network with 12 hospitals with multiple services. They develop a multi-period mathematical programming model to provide options for configuring the system based on population access, critical mass standards, and clinical adjacencies.

Finally, the care delivery is achieved conditioned by the day-to-day operations, which are configured throughout the so-called operational level decisions. In a resource-constrained environment it is important to have rules to prioritize the most important works. Singularly, the staff management decisions play a key role in the service schedule planning for providing health care services in the real-life situations, since staff is generally required to react to unexpected events. In last decade, efforts aimed at redesigning the service delivery for better response to increased levels of unexpected demand. A typical scenario for the latter is the operating room (OR) theater (Guerriero & Guido, 2011)(Cardoen, Demeulemeester, & Beliën, 2010) in hospitals, which is a major cost driver –i.e. surgeons, managers, trustees, nurses… each with their conflicting interests – and the main generator of variance in the surgical activities. The operational patient-customer acuity is usually the driver of scheduling OR (also in emergency departments). However, this policy suffers from the risk of lengthy waiting times for patients with issues that were not life threatening. Increasingly, patients are turning to an emerging model: the retail clinic. Retail clinics have emerged as a low-cost and convenient alternative to the traditional model of ambulatory care, providing a discrete set of acute care and preventive services, on an as-needed basis (Landry & Beaulieu, 2013). The improvement of service scheduling and patient access (medical prescription, appointment, patient admission) are currently the main challenges for healthcare organizations.

In general, a whole-system perspective is required to re-define processes in order to consider the needs of and value accrued by patients at each point in their interaction with the hospital (lean approach (Waring & Bishop, 2010)). To cope with the inherent variability and complex dynamics, this task is many often addressed using optimization models and/or simulation models attempting to mimic the behavior of the system so as to analyze the outcome of different scenarios. Particularly, much attention in the healthcare management literature has been paid on the patient flow and its modeling – refer to (Bhattacharjee & Ray, 2014) for a comprehensive review-.

2.2. Supply Chain Integration

A supply chain system (supply chain, SC for short) is a network that mediates the flow of entities involved in a product life cycle, typically passing through a number of facilities (contributing in the value addition of the product) before being delivered to the end customer (Tayfur& Benjamin, 2007). Such a network consists of nodes and arcs. Nodes represent suppliers, manufacturers, distributors, and vendors (e.g. retail stores), as well as their inventory facilities for storing products and transportation facilities for shipping them among nodes. Arc represent routes connecting the nodes along which goods are transported in a variety of modes (trucking, railways, airway…).

According to (Chopra and Meindl 2007, p. 6), supply chain management (SCM) is "the management of flows between and among all stages of a supply chain to maximize total profitability". Multitude of issues ranging from location, product, and marketing decisions to the management of information exchange and coordination across different stages of the SC are comprised in this definition. Therefore, SCM tackles with a wide range of problems, from strategic problems like logistics network design, to tactical problems like the coordination of inventory and transportation decisions, all the way through day-to-day operational problems like production scheduling, delivery mode selection, and vehicle routing. The SCM systems have been seen as fertile ground for cost reductions (Kumar, Ozdamar, & Ning Zhang, 2008), which owing to the inherent size and complexity of many of these problems makes optimization models to be essential for effective decision making (Ana Muriel & Simchi-Levi, 2003).

One of the most interesting macro-level trends in logistics (both applied and theoretical) is SC integration (also, logistical integration) (Fabbe-Costes, Jahre, & Roussat, 2008). This integration takes many forms, from increasing information flows between different actors in the SC to the transfer of process ownership. According to (Arshinder, Kanda, & Deshmukh, 2008):

> "Generally, a SC consists of different functions: logistics, inventory, purchasing and procurement, production planning, intra- and inter-organizational relationships and performance measures. The rise in papers on SC as well as the case studies in different areas in different industries motivates to study SC issues further. SCs are generally complex with numerous activities usually spread over multiple functions or

> organizations and sometimes over lengthy time horizons. Therefore, it is necessary to overlay a coordination system, which may include: an explicit definition of processes, responsibilities and structures aligned with overall objective of whole SC to bring together multiple functions and organizations."

In practice, the organization restructuring to be addressed must be accompanied by systems and optimization tools, and then the key aspect for SCM are information sharing and SC coordination as vehicle for redesigning decision rights, workflow, and resources between chain members to leverage better performance as a whole (Lee, 2000).

2.2.1. Sourcing Integration

In the SCM literature, the sourcing decisions faced by buyers of goods attempts to minimize an objective function including the transportation cost and procurement cost, both mostly effected by discounts. The quantity discount policy arise as a classical mechanism to conciliate conflicting interests from buyers and suppliers (Arshinder et al., 2008): suppliers want buyers to commit themselves to purchasing large quantities in stable volumes with flexible delivery dates, and buyers prefer supply in small batches due to changing demand and their unwillingness to hold inventories.

Classical price discounts falls into two categories depending on how they are granted: (a) they can be quantity discounts per product and/or order, (b) discounts based in a total purchase volume (whether expressed in total euros or in total number of units), once aggregated over several products and even over several purchasing departments within a company (Stadtler, 2007). Whether (a) or (b), the reduced price is obtained by applying one of the following two discounting approaches: (1) incremental (cumulative approach to price, different prices applied to the units belonging to different discounting levels) or (2) proportional or all-unit discount (once reached a discounting level, the reduced price is applied to all units starting from the first unit). Finally, a buyer may be given the chance of over-declaring the quantity to take advantage of the next discounting level (the so called bumping clause).

There is plenty of SCM literature where quantity discount policies are applied in the inbound transportation or procurement decisions –i.e. the buyer of goods attempts to minimize an objective function including the transportation cost and procurement cost after discount-.

2.2.2. Transportation Decisions

Transportation planning occupies a central place in SCM, as transport and storage of physical goods account for a significant share of the operational cost in a supply network.

In many practical situations, discounts for larger quantities of freight may be applicable to transportation economies of scale, in terms of the number of unit loads delivered. Further, complicating factors as the delay in payments have to be considered in the pricing and ordering decisions. (Sheen & Tsao, 2007) discussed the channel coordination issue under trade credit and freight cost discounts. They assumed that the transportation cost includes quantity discounts due to economies of scale. Glickman and White (2008) addressed the optimal vendor selection problem in a multiproduct supply chain with truckload discount. The study by (Tsao & Lu, 2012) considers quantity discounts for transportation cost between central distribution centers and regional distribution centers in a national-wide network.

The point of view of freight carriers has been studied in (Smith, Campbell, & Mundy, 2007), when addressing the pricing of the freight services to be expedited (namely, define the net rates once discounts are applied) in a the less-than-truckload (LTL) shipments company. According to the authors, the company sets base rates and then negotiates individual customer discounts which purportedly reflect the costs of providing service, competitive pressures, and the anticipated value of the customer relationship. The factors identified in the literature as affecting negotiated rates for LTL shipments, are shown in Figure 1.

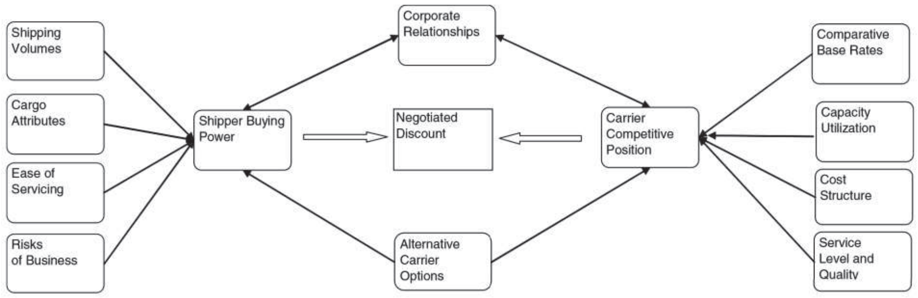


Figure 1 – Factors affecting the negotiated discount (reproduced from (Smith et al., 2007)).

The net freight rate paid by a shipper depends upon the published rate, the discount negotiated with the customer, and the blend of shipments (classification, weight and distance) that occurs. The discount is affected by the relative negotiating power of the two parties (carrier and shipper). It is further affected by the perceived risk (uncertainty) associated with contractual arrangements and by the extent to which the two parties enjoy a mutually constructive relationship that enables them to work synergistically. Contributing to the shipper's buying power in negotiating discounts from published base rates are the volume of business (most generally measured by combination of weight and distance), attributes of cargo affecting the utilization of assets (e.g., density, access to loading facilities, or unbalanced directional flows), ease with which the cargo can be handle and degree of risk associated with the service (Shanahan, 2003). Contributing to the carrier's competitive position are the basic rate structure (which determines the base rates on different shipping lanes), its available capacity on the routes used by the customer, its cost structure for local operation and line hauls, and the service levels (timing and reliability) offered. Contributing to the negotiating power of both parties are the alternative options available from competing carriers and the strength of existing relationships between the parties.

2.2.3. Procurement Trends in Multi-site Organizations

In a wide sense, this thesis concerns to the procurement problem addressed by large multi-site organizations in order to select among multiple suppliers that provide base prices and discounts. In the last decades these organizations have moved to a centralization of their procurement functions, what typically provides the ability to leverage the overall buying power to obtain significant supplier discounts (Balakrishnan & Natarajan, 2014). The business is then allocated across a diminished number of active suppliers, which often offer attractive quantity-based discounts in the expectation of benefitting from economies of scale in their production activities. Another common outcomes are the reduction of the administrative costs and the promotion of better relations with the contracted providers (Xu, Lu, & Glover, 2000). Precisely, the maintenance of long-term partnerships with suppliers has been identified as a competitive strategy pointing to fewer and more efficient providers (Ho, Xu, & Dey, 2010). Further, when the involved product/service has strategic impact on the buyer's business, the supplier selection process should aim at creating a closer relationship with suppliers that make possible improving the results for both parties (Gonçalo&Alencar, 2014).

At a more operative level the procurement settings include realistic issues of lot-sizing: variability on demand, shortage, backorders, lead time, late delivery and also, the role of discounts as a purchase incentive offered by providers that conditions the tradeoffs among objectives in buyer decisions (Taleizadeh, Niaki, &Hoseini, 2009). Complex NP-hard problems arise from stochastic parameters which need to be solved using Meta heuristic algorithms (Taleizadeh, Niaki, & Wee, 2013; Taleizadeh, Wee, &Jolai, 2013). In a whole, the supplier selection process leads usually to complex decision making problems, which could include both quantitative (pricing and discount policy, limited availability), and qualitative (service quality and reliability) criteria, sometimes calibrating the uncertainty risks in the supply. We refer to (Gonçalo&Alencar, 2014), (Ho et al., 2010) and (Aissaoui, Haouari, &Hassini, 2007) for comprehensive reviews on the supplier selection literature.

Aissaoui et al., (2007) claimed that very little attention had been paid to logistics costs in the supplier selection research, once addressed a comprehensive review of supplier selection and order lot-sizing modeling. However, this aspect has been considered in recent studies (Ayhan & Kilic, 2015; Hammami, Temponi, & Frein, 2014; Mansini, Savelsbergh, & Tocchella, 2012; Qin, Luo, Gao, & Lim, 2012). (Mansini et al., 2012; Qin et al., 2012) are bound up to the common practice to out-source the transportation activity to a carrier company on the basis of minimum quantity commitment. (Ayhan & Kilic, 2015; Hammami et al., 2014) include the realistic inclusion of the global marketplace from which selecting suppliers.

In recent years, one of the research streams consists on modeling the complex buyer-supplier discount negotiation (Bichler, Schneider, Guler, & Sayal, 2011; Şen, Yaman, Güler, & Körpeoğlu, 2013; Yin, Nishi, & Grossmann, 2014). In Yin et al. (2014) complexity comes from the flexible purchase agreements guiding contract decisions among a manufacturer of electronic components and its suppliers, with the purpose of sharing risks of uncertain products' demand in a short-life cycle market. In Şen et al. (2013) discount rates are tied to future random events that supplier and buyer can mutually verify, base prices and discounts offered in a bidding process. Bichler et al. (2011) propose a bidding language and an optimization model to express the complex discounts structures that arise in the context of combinatorial auctions.

2.2.4. Tactical Logistic Planning

We can state that for large multi-site organizations, coordinated procurement entails deciding which suppliers to use to meet each site's purchasing needs and sourcing preferences so as to minimize overall purchasing, logistics, and operational costs. Incorporating the interdependence of location, transportation, and inventory decisions leads to complex decision making problems, which could include both quantitative (pricing and discount policy, limited availability), and qualitative (service quality and reliability) criteria, sometimes calibrating the uncertainty risks in the supply.

Relevant to our thesis, we concentrate next on studying papers that apply a tactical planning approach to such decisions.

Supplier selection considering a single-period approach has been applied largely in the literature. Murthy, Soni, & Ghosh (2004) address the supplier selection problem for make-to-order items, when savings in the setup costs associated with producing a bundle of items allow suppliers to offer volume-based discounts for bundles. They make also an interesting review on optimization models for procurement planning. Goossens, Maas, Spieksma, & van de Klundert (2007) address the lot-sizing problem with all-unit discount based on total purchase quantities, presenting a MILP model and a customized branch-and-bound technique, although it is outperformed by a general purpose mixed integer solver when solving medium to large instances.

(Qin et al., 2012) consider also a single-period when addressing a long-term distribution planning problem which allocates freight to international shipping companies offering total quantity discounts. They report a heuristic procedure which provided better performance than commercial mixed integer solvers. Similarly, (Mansini et al., 2012; Qin et al., 2012) apply heuristics to decide simultaneously procurement setting for suppliers offering purchase quantity discounts and transportation costs that are based on truckload shipping rates. Finally, (J. Zhang &Chen, 2013) reports a one-period tactical planning approach quite similar to that needed in our motivating problem. In Zhang & Chen (2013) a telecommunication company plans its next year supplier selection and order policy aiming at the balance between the risk of not meeting the (uncertain) demand, the benefits of having a reduced number of suppliers (offering quantity discounts), and the costs. The authors state a non-linear MILP which is solved to optimality using Generalized Benders Decomposition.

The above works illustrate how in many real-life situations a tactical approach to purchasing decisions is conditioned by transportation costs. It should account for the availability of different transportation modes with different capacities and cost structures between a pair of nodes, and, (ii) it should seek for the tradeoff between transportation and inventory cost. According to (Jaruphongsa, Çetinkaya, & Lee, 2005, 2007), modeling the availability of different transportation modes with different capacities and cost structures between a pair of nodes is a trend in lot-sizing literature from the perspective of tactical SCM.

2.3. Integrated Healthcare Logistics

As healthcare has gradually become a more privatized and contested sector, the development of new organizational changes to meet the opportunities for efficiency has lead healthcare networks to increase the complexity of the entire supply chain. The interest in healthcare supply chains is likely the result of two factors: complexity and potential cost reductions.

Estimates for the cost of logistics related activities generally range from around 30-40% of overall healthcare costs (Nachtmann & Pohl, 2009), second only to labor expenses as a priority for healthcare cost containment. Importantly, supply chain management in the healthcare context is not simply a financial issue; its reliability and speed also has a direct effect on clinical outcomes (Iannone, Lambiase, Miranda, Riemma, & Sarno, 2013).

Relevant to our healthcare planning problems, we next restrict our attention only to papers on logistics management decisions in healthcare.

One general guiding principle of the revised papers has been a call for healthcare logistics to undergo the same mental shift as have its counterparts in other industries: from a secondary function toward acting like (and being thought of as) a key function in meeting the operational and strategic objectives of the organization. The underlying assumption is that the supply chain is that the strategic decisions have been already taken, and the decisions to make correspond to the tactical level.

2.3.1. Extensive Healthcare Networks

In a regional wide context , the collaboration among facilities for a centralization of their procurement functions has been reported as a cost-efficient strategy (Essoussi & Ladet, 2009), while gaining flexibility throughout a resource re-allocation to deal with the fluctuating demand in a wide region.

(Pierskalla, 2005) has studied supply chain for blood, which is not view just as a commodity owing its perishability, the scarce donors and the fact that shortages lead to high costs for society, since they can cause increase mortality rates. This seminal work proposes strategic models for assigning donor areas and transfusion centers to community blood centers, determining the number of community blood centers in a region, locating these centers and coordinating supply and demand. The details on collecting blood, inventory management, blood allocation to hospitals, blood delivery and cross-matching (among blood types) are defined at a tactical level, where matching demand and supply is the major issue (namely, avoiding shortages and aging of blood).

(Şahin, Süral, & Meral, 2007) address the regionalization of blood services on part of the Turkish Red Crescent Society, developing several MILP models to address the location–allocation aspects for the new hierarchical organization structure. One of them consists in redistribute the mobile units to each service region in order to balance the service with respect to the regional populations, which they addressed by means of an integer programming model.

In regionalization, it was shown (Pierskalla, 2005) that economies of scale exist in most of the blood bank management functions. A centralized community blood center is more efficient than a decentralized system. Therefore, another problem concerned is the distribution from blood banks to the different hospitals. Generally speaking, the blood delivery involves a Vehicle Routing Problem to decide the delivery schedules, with the objective of minimizing spoilage and delivery costs (inventory costs not included, since hospitals prefer a high inventory to loss of life due to shortages) and preferring fixed routes (namely, single vehicle visiting the same facilities) because otherwise delivery routes must be recomputed each day. However, in (Hemmelmayr, Doerner, Hartl, & Savelsbergh, 2009) it is reported that when the problem of delivering blood products to Austrian Hospitals, a drastic change which combines flexible routing decisions with a focus on delivery regularity is applied (namely, implying repeating delivery patterns for each hospital) results in cost savings of approximately 30%. They view the problem as a periodic VRP with tour length constraints and no capacity constraints, to conclude that travel costs can be reduced significantly by using this more sophisticated delivery strategy.

Finally, we note that in healthcare context the possible goals of logistic integration may point at procurement improvements (from getting volume-based price incentives in the purchase, to replenishment agreements with increasing responsiveness to variant demands while lowering inventory levels), shipment consolidation or increasing process quality.

3. NETWORK-BASED MODELING APPROACH

The formulation of a problem plays a central role in the solution strategy

Woxley, 1980

For healthcare systems that operate in large, geographically dispersed areas, the quality of the services provided requires the effective management of a complex transportation problem.

Many often healthcare networks address their logistics enhancements relying on Third-Party Logistics partners (3PL), refers to "the organizational practice of contracting-out part of or all logistics activities that were previously in-house" (Selviaridis & Spring, 2007). Through specialization, logistics service providers are assumed to have more expertise in performing logistics function than their customers.

Provided that a substantial part of costs are due to transportation, one critical problem that emerges is how transportation services are selected. In many practical real-life applications a centralized strategy (e.g. a transportation service procurement based on Combinatorial Auction (Sheffi, 2004)) has proven to greatly benefit the objective of providing the framework for cost-efficient operations.

This chapter assumes such a centralized strategy to guide the tactical logistic planning in extensive healthcare networks. We propose an optimization approach to model the key coordination decisions on production, inventory management and transportation. To this aim, we state a MILP model that accounts for the global view of the network layout to provide the coordinating policy among facilities with realistic assessment of long-term operations costs.

3.1. Problem Definition

Assume that the target network distributes commodities (pharmaceutical products, blood, clinical samples, etc…) among a variety of geographically dispersed facilities, thereby with a substantial part of its costs due to transportation. Hence, a key aspect for the integrated management of such networks is the center-led procurement of transportation services. Namely, the network planner needs to purchase a large volume of transportation services over a planning horizon (typically a year), so it is able to get volume-base discounts from express package firms (henceforth, carriers). By assuming long-term quantity commitments, the planner get great quantity-based discounts that make the transportation costs to be piecewise linear functions. Although quantity discounting is typically more advantageous to buyer than to supplier (Samouei, Kheirkhah, &Fattahi, 2014), in our context it is an opportunity for carriers to gain a big long-term customer whose shipments are transported within several fixed destinations on a relatively stable schedule. The planner's view is that by the described integrated approach to logistical management, he is able for taking control of scattered purchasing volumes throughout the whole logistic network to exploit those discounts, while allowing for transportation costs reduction by promoting shipment consolidation.

Finally, let us remark that in spite of defining the next year coordinating policy of production and transportation decisions considering centralized purchasing of shipping services, it is usually more appropriate to leave the day-to-day functions such as placing orders and expediting shipments, reacting to disrupting events, etc. to the facilities – the so-called, decentralized execution (Munson, 2007) -.

In next section, we scope various topics likely to be relevant to our healthcare logistic networks.

3.1.1. Related Work

We began our review of previous literature by considering the core models of network design (Ahuja et al. 1993). For an excellent overview of network-based optimization models in the SCM context refer to (Geunes & Pardalos, 2003).

A strategic optimization model that incorporates the interdependence of location, transportation, and inventory decisions is described by Jayaraman (1998). Here, different transportation modes can be chosen for each connection in the network. Each mode is associated with a commodity-dependent per unit cost and a delivery frequency. Keeping inventory at a plant or warehouse incurs per unit inventory costs, and the amount of inventory held results from the delivery frequencies of the outbound transportation modes used. Note that this still captures temporal consolidation rather coarsely, as theoretically, transportation modes with low delivery frequency could also carry low shipping volumes, making their assumed low per-unit costs unrealistic. The model is solved using standard LP based solvers.

In general terms, a tactical approach to the SCM should deal with optimally utilizing the given infrastructure by choosing services and their associated transportation modes, allocating their capacities to orders, and planning their itineraries and frequency. The latter issues would lead us to map the problem to both time and space, thereby considering space-time network models to accommodate realistics issues in service planning decisions such as different lead-times on different transportation modes. However, in our approximation to logistics healthcare, we specifically concentrate on the so-called Network Flow Planning (NFP). NFP relates to the flow planning decisions addressing the movement of commodities throughout the network (usually modeled as continuous variables, whether link-based representing flow on a link or path-based representing flow on a path –i.e. a sucession of links-).

Our NFP approach is at its heart based on a Minimum-Cost Multicommodity Network Flow Problem (MCNFP), minimizing system-wide costs incurred with the distribution of some commodities from the sources to the demand nodes in the presence of economies of scale in the transportation activity –i.e. a concave MCNFP-. Given the forecasted demand at each destination facility, the tactical logistic plan define the distribution of some commodities (pharmaceutical products, blood, clinical samples,… etc) from the sources to the demand nodes, with transportation costs that exhibit the following complicating feature: each shipping connection will contribute to system-wide costs throughout a non-linear piecewise function of the flow along that connection –i.e. concave MCNFP-. Cohn, Davey, Schkade, Siegel, & Wong (2008) use a similar approach to deal with the cost reduction achieved by a package carrier firm when contracting with a cargo airline; they assume that the cargo airline presents a price offer to each client depending on the cost of the entire load purchased. However, in Cohn et al. (2008) discounts on shipments are a function of the overall flow of the network; in our case study, we use discount factors attached to the flow in each connection. Since each connection can be potentially allocated to a different carrier, the aggregated flow over commodities (total freight) on each connection acts as the discount driver. More specifically, the aggregated flow along that connection is priced according to a piecewise linear function referred as all-unit discount (AUD) (Stadtler, 2007), structure that requires a mixed integer formulation. Further, since capacity constraints appear both on facilities production and transportation, the model that arises is a Capacitated MCNFP with concave costs (CMCNFP-CC).

CMCNFP-CC is a NP-hard problem – see (Guisewite&Pardalos, 1990) for a complexity analysis- for which certain heuristic approaches have been proposed in the literature. Particularly, we refer to (Croxton, Gendron, &Magnanti, 2007) and (Muriel &Munshi, 2004) for structural insight intoMILP formulations of this problem. These authors propose linear programming (LP) heuristic approaches in order to approximate the concave cost function while obtaining good lower bounds. While Muriel &Munshi (2004) report a heuristic solution approach based upon the fact that the LP relaxation of the problem is as strong as the Lagrangian relaxation (applied for example in (Amiri&Pirkul, 1997)), Croxton et al. (2007) approximate the original cost function with its lower convex envelope in the space of commodities. Since for linear routing costs the CMCNFP-CC becomes easier to solve, another heuristic approach consists on approximating geometrically the original cost function by just a line in order to find near-optimal solutions (Hill &Galbreth, 2008).

The aforesaid approaches are relevant to address quite general application problems in the assumption that the objective function is just written in terms of routing costs. However, our quantity discount and carrier selection real-life problems requires a generalized version of this problem considering not only concave routing costs but also operational costs due to product handling, overload and underutilization of facilities.

3.2. Assumptions and Notation

3.2.1. Piecewise Linear Cost Function

In presence of economies of scale in the transportation activity, the shipping costs shape considered in this thesis are as in Figure 2. The first one, referred to as modified all-unit discount (MAUD) cost structure, results from incorporating the bumping clause to the AUD one (Chan, Muriel, Shen, Simchi-Levi, & Teo, 2002).

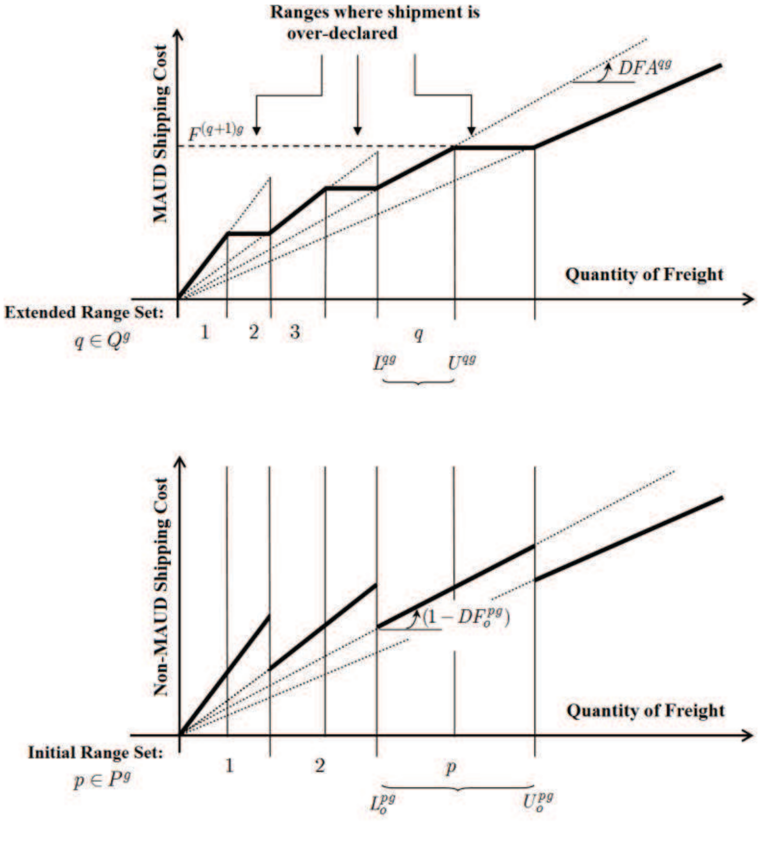


Figure 2 – The transportation costs: *(i)* The modified all-units discount (MAUD) shape, and, *(ii)* The simplified shape ignoring the possibility of over-declaring the quantity of freight committed (AUD).

Let $\overline{G} = (\overline{V}, \overline{L}, K)$ be a directed graph representing the involved distribution network, with commodities set K (namely, the items routed over the network), vertices set $\overline{V}$, links set $\overline{L}$, demands and available capacities for each commodity in K at the vertices, and link capacities (resulting from whether physical or managerial limitations).

Vertices are of different types: some of them have a supply of commodities, others a demand for them. In this model, the flow through a vertex incurs a consumption/processing cost (if the vertex was the destination facility) or a transshipment cost (if the vertex has to redirect the commodity as a next hop before reaching the destination facility). Our model also includes costs for flowing along links, whether they represent routing/shipping costs or outsourcing costs in case of an external purchase of test services.

In next section, we present alternative CMCNFP-CC formulations of the concerned logistic problem with AUD and MAUD piecewise routing costs. Before, we introduce the following notations:

Table 1. Notation

Set of Indices	
K	Set of commodities: $k \in K \mid k = 1 \ldots N_k$.
$\overline{V}$	Set of vertices in graph $\overline{G} = (\overline{V}, \overline{L})$, with elements: $v_i \in \overline{V},\ i = \{0,..,N+1\}$.
$\overline{L}$	Set of links in graph $\overline{G} = (\overline{V}, \overline{L})$, with elements: $(v_i, v_j) \in \overline{L} \mid v_i, v_j \in \overline{V}$, $i = \{0,..,N\}, j = \{1,..,N+1\}$.
V	Set of vertices representing real-life centers, with elements: $v_i \in \overline{V},\ i = \{1,..,N\}$. They are all the vertices in $\overline{V}$ except the demand insertion vertex v_0 and the outsourcing vertex v_{N+1}.

L	Set of links representing real shipping connections, with elements: $(v_i,v_j) \in \bar{L} \mid v_i,v_j \in \bar{V},\ i = \{1,..,N\},\ j = \{1,..,N\},\ i \neq j$.
S_j	Set of indices marking the successors of vertex j: $S_j = \{\ m \mid \exists (v_j,v_m) \in \bar{L}\ \}$.
P_j	Set of indices marking the predecessors of vertex j: $P_j = \{\ m \mid \exists (v_m,v_j) \in \bar{L}\ \}$.
G	Set of package carriers companies considered for shipping services: $g \in G \mid g = 1 \ldots N_g$. They are N_g different carriers.
R^g	Set of discount ranges offered by carrier g: $r \in R^g \mid r = 1 \ldots N_{gr}$. They are N_{gr} different ranges for carrier g, so that the involved discounts depend on the traffic committed on each shipping connection $(v_i,v_j) \in L$, if assigned to be operated by g . These ranges fully partition the feasible volume of total flow on each link: L^{rg} and U^{rg} are the lower and upper bounds on this flow for discount range r , and DF^{rg} is the discount factor itself .
l	Index in which the alternative binary variables of the LogDCC formulation are defined, with $l \in \{1 \ldots \lceil \log_2(N_g \cdot N_{gr}) \rceil\}$.

Model Parameters

a_{ik}	Demand of commodity k at vertex $v_i \in V$.
C_{ik}	Capacity of commodity k at vertex $v_i \in V$.
c^E_{ik}	Execution cost of commodity k at vertex $v_i \in V$.
c^S_{ij}	Shipment cost for link $(v_i,v_j) \in L$.

c_{ik}^{SOC}	Outsourcing cost, standing for the price of type k commodity when processed in a external facility (due to the limited capacity at vertex $v_i \in V$).
c_{ik}^{T}	Transshipment cost of commodity k at vertex $v_i \in V$, which is a fixed per-unit based inventory cost .
u	Percentage to apply to C_{ik} to obtain the threshold that triggers an overload penalty, due to excessive transshipments – i.e. over-transshipment -.
w	Per-unit penalization when over-transshipment.
Y_{ij}	Upper bound for aggregated traffic for $(v_i, v_j) \in L$.
S_{ijk}	Upper bound for a type k traffic for $(v_i, v_j) \in L$.
W_{ik}	Minimal workload, non-zero only at vertex $v_i \in V \mid C_{ik} > 0$.
w^{low}	Per-unit penalization when the established minimal workload W_{ik} is not committed –i.e. underutilization.
L^{rg}	Lower bounds on flow for discount range r referred to carrier g .
U^{rg}	Upper bounds on flow for discount range r referred to carrier g .
DF^{rg}	Discount factor referred to carrier $g \in G$ to be applied if the total flow committed in a certain link is in [L^{rg} , U^{rg}] – i.e. in range $r \in R^g$ -.
MP_{Gadget}^{rg}	Flat-ramp gadget midpoint: transition point from the zero slope segment to the constant slope one.
F^{rg}	Constant bargain zones costs, to be applied if the total flow committed in a certain link is in [MP_{Gadget}^{rg} , U^{rg}] – i.e. in the flat zone of range $r \in R^g$
DFA^{rg}	Commodity-dependent costs, to be applied if the total flow committed in a certain link is in [L^{rg} , MP_{Gadget}^{rg}] – i.e. in the ramp zone of range $r \in R^g$
$GRAY^{rg}$	Gray code assigned to each range $r \in R^g$, where adjacent ranges only differ in one component .

Variables

s_{ijk}	Amount of type k commodities flowing through link $(v_i, v_j) \in L$.
e_{ik}	Amount of type k commodities consumptions at destination facility $v_i \in V$ – i.e. the workload assignment -.
t_{ik}	Amount of type k commodities transshipments in vertex $v_i \in V$.
P_{ik}^{OT}	Contribution to operative costs due to facility $v_i \in V \mid C_{ik} > 0$, when its level of transshipments is above the threshold for the penalty trigger – namely, $t_{ik} > u \cdot C_{ik}$, and consequently, the facility is in the over-transshipment range -.
P_{ik}^{LW}	Contribution to operative costs due to facility $v_i \in V \mid C_{ik}, W_{ik} > 0$ is not committing the specified minimal workload for type k commodities – i.e. $e_{ik} < W_{ik}$, and consequently, facility assigned a too low workload.
z_{ij}^{rg}	1, if aggregated flow on link $(v_i, v_j) \in L$ is operated by carrier g with the discount for range $r \in R^g$; 0 otherwise.
y_{ij}^{rg}	Traffic flowing on link $(v_i, v_j) \in L$, shipped by carrier g and priced according to the discount factor for range $r \in R^g$.
y_{ij}	Aggregated flow on link $(v_i, v_j) \in L$.
g_{ij}^{rg}	Contribution to operative costs due to the MAUD shipping costs on link $(v_i, v_j) \in L$.
μ_{ij}^{rg}	Multiplier $\mu_{ij}^{rg} \in [0, 1]$ in use in order to express the commodity contribution to costs when the load lies into segment $r \in R^g$ -i.e. the aggregated flow on link $(v_i, v_j) \in L$ lies in range $r \in R^g$ -, as a linear combination of the costs at the extreme points of that segment. Variable in use in the DCC and LogDCC models.
λ_{ij}^{rg}	Multiplier $\mu_{ij}^{rg} \in [0, 1]$ in use in order to express the commodity contribution to costs when the load lies in segment $r \in R^g$ -i.e. the

	aggregated flow on link $(v_i, v_j) \in L$ lies in range $r \in R^g$ -, as a linear combination of the costs at the extreme points of that segment. Variable in use in the DCC and LogDCC models.
b_{ij}^{l}	Binary variables in use in the LogDCC model, defined in the following indices: $\forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in L,\ \forall l \in \{1 \ldots \lceil \log_2(N_g \cdot N_{gr}) \rceil \}$.
$MAXb_{ij}$	Binary variable in use in the LogDCC model, equals to the maximum value among the components b_{ij}^{l}.

Notice that for notational convenience we listed symbols specifying the transportation costs derived from the centralized management of carriers in terms of a set $r \in R^g$. This index r stands for one of the two sets of range in use throughout this section, as we explain before –see Figure 2-.

3.3. Problem Formulation

3.3.1. Model for AUD Shipping Costs

Assume economies of scale in the transportation activity according to all-unit discount (AUD), a piecewise linear structure which requires a mixed integer formulation hence.

A formulation of AUD problem of interest is presented in (Andrade-Pineda, Gonzalez-R, &Framinan, 2013), assuming routing costs as in Figure 2 *(ii)*, that are linearized using a multiple choice model approach (Balakrishnan& Graves, 1989) – namely, using a binary indicator variable to make the selection of at most one of the $p \in P^g$ intervals within a carrier offer-.

Next we present a model that has been slightly improved as regards as the preliminary one.

$$
\begin{aligned}
Min\quad & \alpha \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} + \\
& \gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \quad + \quad \delta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} + \\
& \eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik} + \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{p \in P^g} \sum_{g \in G} (1 - DF^{pq}) \cdot y_{ij}^{pg}
\end{aligned}
\tag{1}
$$

s.t.

$$s_{\mathrm{0ik}} = a_{ik} \qquad , \forall k \in K,\ \forall i \,\Big|\, v_i \in \{\ V \,\Big|\, a_{ik} > 0\ \} \tag{2}$$

$$e_{ik} \le C_{ik} \qquad , \forall k \in K,\ \forall i \neq 0 \ / \ v_i \in V \tag{3}$$

$$- \sum_{\substack{i \in P_j \\ i \neq 0}} s_{jlk} + e_{jk} + t_{jk} = 0 \qquad , \forall k \in K, \forall j \ / \ v_j \in \{ V \mid C_{ik} > 0\} \tag{4}$$

$$\sum_{\substack{i \in P_j \\ i \neq 0}} s_{ijk} - \sum_{l \in S_j} s_{jlk} - e_{jk} = 0 \qquad , \forall k \in K,\ \forall j \ / \ v_j \in V \neq v_0 \tag{5}$$

$$- \sum_{k \in K} s_{ijk} + y_{ij} = 0 \qquad , \forall i, j \ / \ v_i \neq v_o, (v_i, v_j) \in L \tag{6}$$

$$y_{ij} \le Y_{ij} \qquad , \forall i, j \ / \ v_i \neq v_o, (v_i, v_j) \in L \mid c_{ij}^{s} > 0 \tag{7}$$

$$s_{ijk} \le S_{ijk} \qquad , \forall k \in K, \forall i, j \ / \ v_i \neq v_o, (v_i, v_j) \in L \tag{8}$$

$$w \cdot t_{ik} - P_{ik}^{OT} \le w \cdot u \cdot C_{ik} \qquad , \forall k \in K, \forall i \,\Big|\, v_i \in \{\ V \,\Big|\, C_{ik} > 0\} \tag{9}$$

$$- w^{low} \cdot e_{ik} - P_{ik}^{LW} \le - w^{low} \cdot W_{ik} \qquad , \forall k \in K, \forall i \,\Big|\, v_i \in \{\ V \,\Big|\, C_{ik}, W_{ik} > 0\} \tag{10}$$

$$\sum_{g} \sum_{p \in P^g} z_{ij}^{pg} \le 1 \qquad , \forall i \neq 0, j \neq N + 1 \ / \ (v_i, v_j) \in L \tag{11}$$

$$- y_{ij}^{pg} + L^{rg} \cdot z_{ij}^{pg} \le 0 \qquad , \forall p, g, \forall i, j \ / (v_i, v_j) \in L \tag{12}$$

$$y_{ij}^{pg} - U^{rg} \cdot z_{ij}^{pg} \le 0 \qquad , \forall p, g, \forall i, j \ / (v_i, v_j) \in L \tag{13}$$

$$y_{ij} = \sum_{g} \sum_{p \in P^g} y_{ij}^{pg} \qquad , \forall i, j \ / (v_i, v_j) \in L \tag{14}$$

$$y_{ij}^{pg} \ge z_{ij}^{pg} \qquad , \forall p, g, \forall i, j \ / (v_i, v_j) \in L \tag{15}$$

$$e_{ik}, s_{ijk}, t_{ik}, y_{ij}, P_{ik}^{OT}, P_{ik}^{LW} \ge 0 \qquad , y_{ij}^{pg} \ge 0,\ z_{ij}^{pg}\ binary \ge 0 \tag{16}$$

The non-convex objective function embeds shipping costs, transshipment costs, processing and outsourcing costs, and additional operational costs when laboratories receive too few or too many samples to be analyzed. Notice we have considered it to be a linear combination (1) with weights $\alpha, \beta, \gamma, \delta, \eta, \varphi$ that are instance-dependent parameters.

Demand is injected from v_0 'fictitious vertex' – see constraints (2) - and then balance equations – see constraints $(4-5)$ - allow for the workload assignment to facilities as well as for the evaluation of transshipments in every real-life center in the distribution network. When a facility is set at a too-low workload, the underutilization penalty is imposed by constraints (10). Similarly, when there is an excess of transshipments at a facility, the overload penalty is imposed by constraints (9). Notice that the decision-maker can impose traffic bounds – see constraints $(7-8)$ - and capacity constraints for the processing levels – including the outsourcing vertex, see constraints (3) -.

Dislike the model in Andrade-Pineda et al. (2013), we let the above model determining that a certain connection is not assigned a carrier –see (11) - and include a valid inequality –see (15) - to code that a null load implies a null indicator variable (Sridhar, Linderoth, & Luedtke, 2013), thereby benefiting the speed of computations. Besides, $(9-10)$ are Set Ordering Set 1 (SOS1) constraints linearizing the respective piecewise lineal penalty functions corresponding to overload and underutilization of facilities.

3.3.2. Model for MAUD Shipping Costs

Now, let us assume economies of scale in the transportation activity according to the modified all-unit discount (MAUD) (Chan, Muriel, Shen, Simchi-Levi, & Teo, 2002) in Figure 2 part *(i)*. This is the cost structure used in Papers #3 and #4.

The most straightforward idea for the realistic assessment of MAUD transportation costs is applying a multiple choice approach as in the above shown model -see Table 2 for a numerical example-.

Table 2. Numerical example of the increasing number of ranges arisen from the MAUD shipping costs.

Discounts Offered by a Carrier with sending commitment					**Discounts Offered by a Carrier with sending commitment**				
$p \in P^g$	L_0^{pg}	U_0^{pg}	$1 - DF_0^{pg}$		$q \in Q^g$	L^{qg}	U^{qg}	DFA^{qg}	F^{qg}
p1	0	500	1.000		*q1*	0	465	1	0
p2	501	1000	0.93		*q2*	466	500	0	465.93
p3	1001	1850	0.880		*q3*	501	947	0.93	0
p4	1851	2500	0.800		*q4*	948	1000	0	880.88
p5	2501	4500	0.730		*q5*	1001	1682	0.88	0
p6	4501	9999	0.650		*q6*	1683	1850	0	1480.8
p7	10000	50000	0.456	→	*q7*	1851	2282	0.80	0
					q8	2283	2500	0	1825.73
					q9	2501	4007	0.73	0
					q10	4008	4500	0	2925.65
					q11	4501	7015	0.65	0
					q12	7016	9999	0	4560
					q13	10000	50000	0.456	0

Unfortunately, proceeding like this results in a MILP model that does not behave well with the state-of-the-art solvers. Since the extended problem greatly increases the number of binary indicators variables (almost the double), the problem becomes intractable for many instances of realistic size.

To address the deficiency of such a straightforward modeling approach, in (Andrade-Pineda, Canca, & Gonzalez-R, 2015) we have proposed a novel modeling technique based on the identification of flat-ramp gadgets.

3.3.2.1. A Flat-Ramp Gadget-Based Model of MAUD

Let's recall here the features of MAUD shape shown in Figure 1. As illustrated there, the extended set $q \in Q^g$ is related to $p \in P^g$, the range set in which carrier firms present their offers. Particularly, odd index q indicates a ramp of cost proportional to $DFA^{qg} = (1 - DF_0^{(\frac{q+1}{2})g})$, whereas even index q indicates flat segment of cost $F^{qg} = L_0^{(\frac{q}{2}+1)g} \cdot (1 - DF_0^{(\frac{q}{2}+1)g})$.

In view of the deficient tractability exhibited by a straightforward multiple choice approach written in the extended set $q \in Q^g$ (namely, almost double the number or binary indicator variables as regards as the AUD case), we propose in this thesis a new modeling technique that takes advantage of considering the MAUD shape as a composition built on the basis of flat-ramp gadgets.

A very similar gadget has been proposed in (Harks, König, Matuschke, Richter, & Schulz, 2012), which handles the MAUD transportation tariffs on the basis of generating a bundle of auxiliary parallel links. If we apply the approach by Harks et al. (2014), then we would turn the problem into a NFP requiring exactly the same number of binaries (to be able to impose the fixed/flat costs considered in their pattern expansion of every original link) written on a larger graph $\overline{\overline{G}} = (\overline{\overline{V}}, \overline{\overline{L}}, K)$, despite the structure of constraints will be different. However, increasing the yet large amount of links expected in our target network to be solved leads to extend the number of variables (and related constraints), particularly the integer ones, what is not the best option.

Differently, we propose the use of a modeling-based gadget connected to a modified range set $r \in R^g$ –see Figure 3 – to address the MAUD shape in a manner that cuts down the number of indicator binary variables (and consequently the number of integer constraints) whereas remains the graph the same. Furthermore, this novel approach can be useful to gain computational efficiency in many practical real-world problems effected by economies of scale.

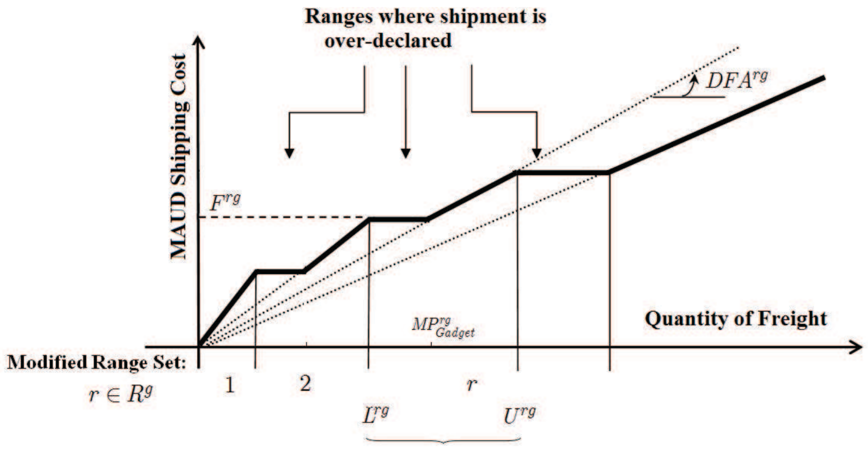


Figure 3 – The MAUD shape and the consideration of a reduced amount of intervals based on the use of flat-ramp gadgets.

Table 3 – Numerical example of the gadget based reduction of the required binary indicator variables: from the 13 extended ranges in Table 2, to only 7 modified ranges.

$r \in R^g$	L^{rg}	MP^{rg}_{Gadget}	U^{rg}	DFA^{rg}	F^{rg}
r1	*0*	*0*	*465*	*1.000*	*0*
r2	*466*	*500*	*947*	*0.930*	*465.93*
r3	*948*	*1000*	*1682*	*0.880*	*880.88*
r4	*1683*	*1850*	*2282*	*0.800*	*1480.80*
r5	*2283*	*2500*	*4007*	*0.730*	*1825.73*
r6	*4008*	*4500*	*7015*	*0.650*	*2925.65*
r7	*7016*	*9999*	*50000*	*0.456*	*4560.00*

Next, we present the novel formulation. For the sake of clarity we remark that the index r is henceforth referred to the modified ranges that arise from the gadget-based modeling approach –see Figure 3-.

$$\begin{aligned} F_{MC} = Min \ \ & \alpha \cdot \sum_{k\in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k\in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} + \\ & \gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \quad + \quad \delta \cdot \sum_{k\in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} + \\ & \eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik} \quad + \quad \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{r \in R^g} \sum_{g \in G} g_{ij}^{rg} \end{aligned} \tag{17}$$

s.t.

$$s_{0\mathrm{ik}} = a_{ik} \qquad ,\forall k \in K,\ \forall i \,\middle|\, v_i \in \{\ V \,\middle|\, a_{ik} > 0\ \} \tag{18}$$

$$e_{ik} \leq C_{ik} \qquad ,\forall k \in K,\ \forall i \neq 0 \ / \ v_i \in V \tag{19}$$

$$-\sum_{\substack{i\in P_j \\ i\neq 0}} s_{jlk} + e_{jk} + t_{jk} = 0 \qquad , \forall k \in K, \forall j \ / \ v_j \in \{\ V \mid C_{ik} > 0\} \tag{20}$$

$$\sum_{\substack{i\in P_j \\ i\neq 0}} s_{ijk} - \sum_{l \in S_j} s_{jlk} - e_{jk} = 0 \qquad ,\forall k \in K,\ \forall j \ / \ v_j \in V \neq v_0 \tag{21}$$

$$-\sum_{k\in K} s_{ijk} + y_{ij} = 0 \qquad ,\forall i, j \ / \ v_i \neq v_o, (v_i, v_j) \in L \tag{22}$$

$$y_{ij} \leq Y_{ij} \qquad ,\forall i, j \ / \ v_i \neq v_o,(v_i, v_j) \in L \mid c_{ij}^{s} > 0 \tag{23}$$

$$s_{ijk} \leq S_{ijk} \qquad ,\forall k \in K, \forall i, j \ / \ v_i \neq v_o,(v_i, v_j) \in L \tag{24}$$

$$w \cdot t_{ik} - P_{ik}^{OT} \leq w \cdot u \cdot C_{ik} \qquad ,\forall k \in K, \forall i \,\middle|\, v_i \in \{\ V \,\middle|\, C_{ik} > 0\} \tag{25}$$

$$-w^{low} \cdot e_{ik} - P_{ik}^{LW} \leq -w^{low} \cdot W_{ik} \qquad ,\forall k \in K, \forall i \,\middle|\, v_i \in \{\ V \,\middle|\, C_{ik}, W_{ik} > 0\} \tag{26}$$

$$\sum_{g} \sum_{r\in R^g} z_{ij}^{rg} \leq 1 \qquad ,\forall i \neq 0, j \neq N+1 \ / \ (v_i, v_j) \in L \tag{27}$$

$$-y_{ij}^{rg} + L^{rg} \cdot z_{ij}^{rg} \leq 0 \qquad ,\forall r, g, \forall i, j \ /(v_i, v_j) \in L \tag{28}$$

$$y_{ij}^{rg} - U^{rg} \cdot z_{ij}^{rg} \leq 0 \qquad ,\forall r, g, \forall i, j \ /(v_i, v_j) \in L \tag{29}$$

$$y_{ij} = \sum_{g} \sum_{r\in R^g} y_{ij}^{rg} \qquad ,\forall i, j \ /(v_i, v_j) \in L \tag{30}$$

$$g_{ij}^{rg} \geq F^{rg} \cdot z_{ij}^{rg} \qquad ,\forall r, g, \forall i, j \ /(v_i, v_j) \in L \tag{31}$$

$$g_{ij}^{rg} \geq DFA^{rg} \cdot y_{ij}^{rg} \qquad ,\forall r, g, \forall i, j \ /(v_i, v_j) \in L \tag{32}$$

$$y_{ij}^{rg} \geq z_{ij}^{rg} \qquad ,\forall r, g, \forall i, j \ /(v_i, v_j) \in L \tag{33}$$

$$e_{ik}, s_{ijk}, t_{ik}, y_{ij}, P_{ik}^{OT}, P_{ik}^{LW}, g_{ij}^{rg} \geq 0 \ , y_{ij}^{rg} \geq 0,\ z_{ij}^{rg}\ binary \geq 0 \tag{34}$$

Notice it is a multiple choice approach using the reduced binary indicator variables z_{ij}^{rg} to choose the appropriate gadget according to the flow throughout link (v_i, v_j), that can accurately reflect the incurred costs due to that load as a variable g_{ij}^{rg}. It is well-known that this kind of increasing slope transitions (flat → ramp) can be modeled taking the minimum of the fixed value (flat) resulting from over-declaring the quantity of freight committed and the load-dependent linear function (ramp) and hence, avoiding the inclusion of additional binary variables and the constraints which are exclusive to them.

4. SOLUTION STRATEGIES

Once created the network model addressing the target problem, in this chapter the concern is how best to solve it in practical instances. Note that our models in former chapter were basically LP problems extended with integer variables and extra constraints in a combinatorial flavor. Specifically, we have added these complicating variables for modeling the non-linearity owing to the economies of scale in the transportation costs.

Although combinatorial problems are sometimes well-solved by state-of-the-art commercial solvers, tractability issues appear with large-scale instances. The most successful algorithm included in such commercial packages is the branch-and-bound method. However, as we show next, using the method in a way suited to the problem features can result in dramatic improvements over other less “intelligent” strategies.

Precisely, the structural properties of the models stated has been the key aspect from which different solutions strategies have been intended to efficiently solving large size instances of the combinatorial formulation involved.

4.1. Problem’s Structure: Bordered Block Diagonal

Notice that the CMCNFP-CC models presented in the former chapter exhibit the following bordered block diagonal structure:

$$Min_{\boldsymbol{x}_r^V, \boldsymbol{y}_s^L, \boldsymbol{y}_q^L} \quad \boldsymbol{h}_r \cdot \boldsymbol{x}_r^V + \quad \boldsymbol{g}_s \cdot \boldsymbol{y}_s^V + \quad \boldsymbol{d}_q^L \cdot \boldsymbol{y}_q^L \tag{35}$$

$s.t.$

$$\boldsymbol{H}_{mr} \cdot \boldsymbol{x}_r^V + \quad \boldsymbol{G}_{ms} \cdot \boldsymbol{y}_s^L + \boldsymbol{D}_{mq} \cdot \boldsymbol{y}_q^L \leq \boldsymbol{b}_m \tag{36}$$

$$\boldsymbol{E}_{nq} \cdot \boldsymbol{y}_q^L \leq \boldsymbol{e}_n \tag{37}$$

$$\boldsymbol{x}_r^V, \boldsymbol{y}_s^L \in \mathbf{R}_+^{r+s}, \quad \boldsymbol{y}_q^L \in \mathbf{Z}_+^q \tag{38}$$

, where the superscripts V and L denote whether a variable is concerning a vertex or a link. Notice also that every matrix and vector appears subscripted with the appropriate dimensions. Assume that: (i) vector x_r^V encloses the variables capturing the level of activity at each facility $v \in V$ – e.g. production or inventory-, with different capacity level for each commodity, (ii) vector y_s^L represents the commodities flows (both aggregated and disaggregated) over the links, constrained to certain capacity bounds, and (iii) vector y_q^L represents an integer subset of variables necessary to incorporate carrier selection decisions in each link , according to a discount policy based on the volume of commodities. The transportation cost within the objective function (35) – denoted $d_q^L \cdot y_q^L$ - is a concave piecewise-linear function, hence. In addition, the objective function collects the contribution due to link flows and activity levels for each commodity at each facility in a linear form through constant unitary costs h_r and g_s , respectively. The feasibility region for the integer vector y_q^L is first defined by the block of linear constraints (37). Notice that all the variables except y_q^L have been considered to be continuous because at the optimum the solution will be integer due to the underlying pure network flow structure. The constraints that provide this structure are embedded in the first block of linear constraints (36), representing flow balances and bounds on variables. The rest of these constraints act as links[1] among the integer variables y_q^L and the continuous variables x_r^V, y_s^L.

4.1.1. Variable Decomposition for AUD Problems

Assume the problem of interests formulated according to $(1-16)$. We can split into continuous and integer parts and hence, restate it in the following compact form:

---

[1] In our concerned problem, linking constraints accomplish the specific filling of the priced flows embedded in y_q^L based on the continuous variables values x_r^V, y_s^L, thereby refining which integer realizations are feasible according to the whole structure. We refer to chapter 5 for the illustrative example of the ANCL planning problem.

$$[MILP] \quad Min_{x_p, y_q} \quad c_p \cdot x_p + d_q \cdot y_q \tag{39}$$

$$s.t.$$

$$A_{mp} \cdot x_p + B_{mq} \cdot y_q \leq b_m \tag{40}$$

$$C_{op} \cdot x_p \leq c_o \quad , x_p \in \mathbf{R}_+^p \tag{41}$$

$$E_{nq} \cdot y_q \leq e_n \quad , y_q \in \mathbf{Z}_+^q \tag{42}$$

, where the continuous variables are all embedded into a p-dimensional vector ($x_p \equiv [x_r^V, y_s^L]$ which contributes to the objective function linearly with a constant vector $c_p \equiv [h_r, g_s]$) and the q-dimensional vector of complicating variables appears renamed as $y_q \equiv y_q^L$. Similarly, for notational convenience we have renamed the all-unit discounted prices as $d_q \equiv d_q^L$.

We devise a variable decomposition strategy, where the carrier-discount selections represent the main logistic decisions (attained now in terms of integer complicating variables), whereas flows and activity levels continuous variables x_p are settled in a lower level of decision. Indeed, it is a solution strategy that comprises an iterative coordination of these two levels of decision:

- ***A lower level*** (*"Which flows and activity levels*?") that, for given carrier-discount choices, computes the associated optimal values for the "easy LP problem" on a vector of continuous variables x_p as well as pricing information (dual variables) and an upper bound for the original problem.
- ***A higher level*** (*"Which carrier-discount selections*?"), consisting of a relaxed version of the original problem with the set of binary variables and its associated constraints (still a "difficult MILP problem"). At every iteration, this relaxed version is enriched using the outcome of the *lower level* to append a violated cut on the space of the complicating variables. The augmented relaxed problem is then solved to provide a new lower bound for the original problem, as well as a new tentative carrier-discount choice to be used in the next iteration's *lower level* problem.

4.1.2. Generalized Bender Decomposition on a Bilinear Reformulation of AUD Problems

Aiming at a more agile resolution procedure, we can restate the concerned CMCNFP-CC $(1-16)$ as a linearly constrained MIBLP model – see (Adams & Sherali, 1993) for an in-depth numerical study of general MIBLPs-, which is algebraically written in the following compact form:

$$[MIBLP] \quad Min_{\,\boldsymbol{x_p},\boldsymbol{z_q}} \quad \boldsymbol{c_p} \cdot \boldsymbol{x_p} \quad + \quad \boldsymbol{d_q} \cdot \boldsymbol{x_p} \cdot \boldsymbol{z_q} \tag{42}$$

$$s.t.$$

$$\boldsymbol{A_{mp}} \cdot \boldsymbol{x_p} + \quad \boldsymbol{B_{mq}} \cdot \boldsymbol{z_q} \leq \boldsymbol{b_m} \tag{43}$$

$$\boldsymbol{C_{op}} \cdot \boldsymbol{x_p} \leq \boldsymbol{c_o} \quad , \quad \boldsymbol{x_p} \in \mathbf{R}_+^{\boldsymbol{p}} \tag{44}$$

$$\boldsymbol{E'_{nq}} \cdot \boldsymbol{z_q} \leq \boldsymbol{e'_n} \quad , \quad \boldsymbol{z_q} \in \{0,1\}^{\boldsymbol{q}} \tag{45}$$

Next, we explicitly present the non-traditional formulation equivalent to the MILP model $(1-16)$ on which we have applied our GBD iterative algorithm:

$$F_{BP} = Min \ f_{BP}(\boldsymbol{x_p},\boldsymbol{z_q}) \quad = \quad \boldsymbol{c_p} \cdot \boldsymbol{x_p} + \boldsymbol{d_q} \cdot \boldsymbol{x_p} \cdot \boldsymbol{z_q}$$

$$\begin{aligned} Min \ \ & \alpha \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} + \\ & \gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \quad + \delta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} + \\ & \eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik} \ + \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{p \in P^g} \sum_{g \in G} (1 - DF^{pq}) \cdot y_{ij} \cdot z_{ij}^{pg} \end{aligned} \tag{46}$$

$s.t.$

$$\begin{array}{l} \boldsymbol{A_{mp}} \cdot \boldsymbol{x_p} \\ + \\ \\ \boldsymbol{B_{mq}} \cdot \boldsymbol{z_q} \\ \\ \leq \boldsymbol{b_m} \end{array} \left\{ \begin{array}{lll} & Eq. \quad (2)-(10) & \\ y_{ij} - M \cdot \sum_{g \in G} \sum_{r \in P^g} z_{ij}^{pg} \leq 0 & ,(v_i, v_j) \in L \mid c_{ij}^{s} > 0 & (47) \\ - y_{ij} + \quad L^{pg} \cdot z_{ij}^{pg} \leq 0 & ,\forall p, g, (v_i, v_j) \in L \mid c_{ij}^{s} > 0, L^{pg} > 0 & (48) \\ y_{ij} - U^{pg} \cdot z_{ij}^{pg} - Y_{ij} \cdot (1 - z_{ij}^{pg}) \leq 0 & ,\forall p, g, (v_i, v_j) \in L \mid c_{ij}^{s} > 0 & (49) \end{array} \right.$$

$$\begin{array}{l} \boldsymbol{E_{lq}}\cdot \boldsymbol{z_q} \\ \le \\ \boldsymbol{e_l} \end{array} \left\{ \begin{array}{ll} z_{ij}^{p_1 g_1} + z_{ij}^{p_2 g_2} \le 1 & ,p_1 \in P^{g_1}, p_2 \in P^{g_2}, p_1 \neq p_2, \\ & \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in L \qquad (50) \\ \displaystyle\sum_{g \in G} \sum_{r \in R^g} z_{ij}^{rg} = 1 & , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in L \mid c_{ij}^{s} > 0 \qquad (51) \end{array} \right.$$

$$\begin{array}{l} \boldsymbol{x_p} \in \mathbf{R}_{+}^{\boldsymbol{p}} \\ \boldsymbol{z_q} \in \mathbf{Z}_{+}^{\boldsymbol{q}} \end{array} \left\{ \begin{array}{l} e_{ik}, s_{ijk}, t_{ik}, y_{ij}, P_{ik}^{OT}, P_{ik}^{LW} \ge 0 \\ z_{ij}^{pg} \; binary \ge 0 \end{array} \right. \qquad (52)$$

Observe that here the only complicating variables are the binary variables z_{ij}^{pg}, and that the feasibility region implied by constraints (51) is such that each connection is operated by exactly one carrier. Again, we use valid inequalities in order to tighten relaxations – see constraints (27) -. Certain constraints link complicating variables $\boldsymbol{z}_q = [z_{ij}^{pg}]$ and continuous variables $\boldsymbol{x_p} = [P_{ik}^{OT}, P_{ik}^{LW}, e_{ik}, t_{ik}, s_{ijk}, y_{ij}]$ – see constraints $(47-49)$ -. Notice that constraints $(47-50)$ impose the required centralized management of package carrier services as follows. Constraints (48) imply that when the aggregated flow y_{ij} is zero, then none of the binary variables z_{ij}^{pg} are activated. Constraints (47) together with constraints (48) ensure that the absence of selected carrier/range –i.e. $z_{ij}^{pg} = 0 \;\; , \forall p, g$ - implies null aggregated flow.

Similarly, if the aggregated flow is $y_{ij} > 0$, constraints (47) warrantee that exactly one pair carrier/range is selected, according to the lower and upper limits for the discount range imposed by constraints $(47-49)$.

Finally, constraints (52) indicate that all the decision variables are continuous and positive, with the exception of the complicating binary variable disturbing the network flow structure. Notice that within the vector of easy variables $\boldsymbol{x_p}$, there are components that are continuous by nature (P_{ik}^{OT}, P_{ik}^{LW}) whereas others do not need to be forced to integer ($e_{ik}, t_{ik}, y_{ij}, s_{ijk}$) because the special network flow structure of constraints $(2-10)$ ensures integrality at the optimum, provided that the values for capacities, demands and bounds ($Y_{ik}, S_{ijk}, L^{pg}, U^{pg}$) are also integer.

4.2. Addressing Tractability Issues for MAUD Problems

The relaxation of the sending commitment condition makes even more difficult solving the network problem concerned in this research. Constructing a valid MILP formulation following the basic seminal multiple choice approach (namely, written in extended set $q \in Q^g$ in Figure 1) is possible, but it reduces the effectiveness of commercial solvers significantly. Further, this basic modeling approach can lead to intractability when applied to large instances. The two drawbacks of the arising MILP are its large size – increased number of constraints and binary variables as consequence of the $n-1$ newly introduced discount intervals (see Figure 2)- and, the deep and unbalanced branch-and-bound tree that is obtained from the LP solver – consequence of branching on the binary variables (Geißler, Martin, Morsi, &Schewe, 2012)-.

Firstly, one of the key issues that causes intractability is addressed by the multiple choice approach on the modified range set $r \in R^g$, which significantly reduces the number of intervals where defining binary indicator variables. When the novel gadget is considered joined to a multiple choice approach linearizing the non-convex MAUD transportation costs, an alternative formulation – see model $(17-34)$ in Chapter 3 - emerges which outperforms the seminal one. Comparing to the classical multiple choice method stated in range $q \in Q^g$, our identification of flat-ramp gadgets significantly reduces the number of intervals where defining binary indicator variables and the constraints which are exclusive to them.

To address the second deficiency, along this section we explore potential opportunities to improve the branch-and-bound mechanism of LP based solvers, once the novel gadget technique has been applied. A two-steps procedure is followed which produces two alternative methods to piecewisely linearize the MAUD function instead of MC:

(i). The first one consists on the use of a Disaggregated Convex Combination (DCC) approach – see (Croxton, Gendron, & Magnanti, 2003) for a comparison with the multiple choice one- and then,

(ii). The second one copes with the task of formulating the DCC model using fewer binary variables. As it has been pointed out recently (Keha, De Farias Jr., & Nemhauser, 2006; Li, Huang, & Fang, 2013), when considering n discount ranges, one can formulate the adjacency conditions required in a DCC model using just $\lceil \log_2 n \rceil$ binaries, instead of representing the discount range selection with n binaries.

It is worth to remark that while *(i)* introduces certain adjacency constraints, *(ii)* applies a logarithmic disaggregated convex combination method similar to that devised in Vielma & Nemhauser (2011) in order to no longer use the auxiliary binary indicator variables but incorporate the adjacency constraints directly in the branching (Geißler et al., 2012). More precisely, we have applied the logarithmic method in Li et al. (2013), which has been further modified to get a new formulation (henceforth LogDCC), whose LP relaxation has extreme points that all satisfy the adjacency property. This is the so-called locally ideal property (Sridhar et al., 2013) and, according to our computational experience, makes our variant exhibiting enhanced performance.

4.2.1. DCC Method to Piecewisely Linearize MAUD Shapes

The commodity-dependent contribution of flows can be incorporated in a different manner. Making use of the fact that the cost of a flow that lies in a certain segment is a convex combination of the cost of its two extremes, that contribution can be written as a function of multipliers $\mu^{rg}, \lambda^{rg} \in [0,1]$ –see (56) -.

This is the disaggregated convex combination (DCC) linearization method, which is appropriate for addressing continuous and semi-continuous piecewise linear functions. In our motivating problem a lower semi-continuous shape stands for commodity-dependent costs –see (32) -. When applied to our challenging planning problem it results:

$$
\begin{aligned}
F_{DCC} = Min\ \ & \alpha \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} + \\
& \gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \quad + \quad \delta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} + \\
& \eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik} \quad + \quad \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{r \in R^g} \sum_{g \in G} g_{ij}^{rg}
\end{aligned}
\tag{55}
$$

s.t.

$$(18) - (26), (31)$$

$$z_{ij}^{rg} = \lambda_{ij}^{rg} + \mu_{ij}^{rg} \qquad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in L \tag{56}$$

$$y_{ij} = \sum_{g} \sum_{r \in R^g} DFA^{rg} [\lambda_{ij}^{rg} \cdot U^{rg} + \mu_{ij}^{rg} \cdot L^{rg}] \qquad , \forall i, j \,/ (v_i, v_j) \in L \tag{55}$$

$$g_{ij}^{rg} \geq DFA^{rg} \cdot [\lambda_{ij}^{rg} \cdot U^{rg} + \mu_{ij}^{rg} \cdot L^{rg}] \qquad , \forall r, g, \forall i, j \,/ (v_i, v_j) \in L \tag{56}$$

$$\lambda_{ij}^{rg} \cdot U^{rg} + \mu_{ij}^{rg} \cdot L^{rg} \geq z_{ij}^{rg} \qquad , \forall r, g, \forall i, j \,/ (v_i, v_j) \in L \tag{57}$$

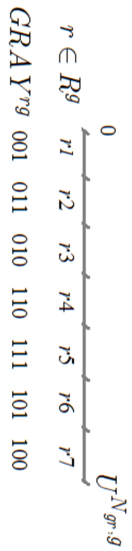
$$e_{ik}, s_{ijk}, t_{ik}, y_{ij}, P_{ik}^{OT}, P_{ik}^{LW} \geq 0, \quad y_{ij}^{rg} \geq 0, \quad \lambda_{ij}^{rg}, \mu_{ij}^{rg} \geq 0, \quad z_{ij}^{rg}\ binary \geq 0 \tag{58}$$

4.2.2. LogDCC Method to Piecewisely Linearize MAUD Shapes

The third method proposed to address the lower semi-continuous piecewise linear optimization problem, follows the ideas first devised in Vielma, Keha, & Nemhauser (2008) to reduce the number of binary variables and constraints of DCC by using a logarithmic representation of the MAUD shape. This method has been formerly applied for the case of discontinuous objective function in Vielma & Nemhauser (2011).

Let us denote n to the $N_g \cdot N_{gr}$ definition intervals of the MAUD piecewise linear function. In order to employ new binary variables $b_{ij}^1, b_{ij}^2, \ldots, b_{ij}^l, \ldots, b_{ij}^{\lceil \log_2(n) \rceil}$, the key idea is to use a Gray code to encode each interval, which we do by defining an injective function $GRAY: \{1 \ldots n\} \longrightarrow \{0,1\}^{\lceil \log_2(n) \rceil}$ with the additional property that for any number $k \in \{1 \ldots n\}$ the vectors $GRAY(k)$ and $GRAY(k+1)$ only differ in one component.

Table 4 – Gray codes in use in LogDCC: the all-zero code reserved to the non-load case, which is helpful to accomplish a locally ideal formulation.



$r \in R^g$	L^{rg}	U^{rg}	DFA^{rg}	F^{rg}
r1	0	465	1.000	0
r2	466	947	0.930	465.93
r3	948	1682	0.880	880.88
r4	1683	2,282	0.800	1480.80
r5	2283	4007	0.730	1825.73
r6	4008	7015	0.650	2925.65
r7	7016	50,000	0.456	4560.00

Our third alternative formulation (LogDCC) for the challenging planning problem is stated as follows:

$$F_{LogDCC} = Min \;\; \alpha \cdot \sum_{k\in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} +$$

$$\gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \quad + \quad \delta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} +$$

$$\eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik} \quad + \quad \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{r \in R^g} \sum_{g \in G} g_{ij}^{rg} \tag{59}$$

$s.t.$

$$(18) - (26), (55), (56)$$

$$b_{ij}^{l} = \sum_{g} \sum_{r \in R^g} Bit^{l}(GRAY^{rg}) \cdot [\lambda_{ij}^{rg} + \mu_{ij}^{rg}] \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in L,$$
$$\forall l \in \{1 ... \lceil \log_2(N_g \cdot N_{gr}) \rceil \} \tag{60}$$

$$\sum_{g} \sum_{r \in R^g} [\lambda_{ij}^{rg} + \mu_{ij}^{rg}] = MAXb_{ij} \qquad , \forall i, j \,/ (v_i, v_j) \in L \tag{61}$$

$$g_{ij}^{rg} \geq F^{rg} \cdot [\lambda_{ij}^{rg} + \mu_{ij}^{rg}] \qquad , \forall r, g, \forall i, j \,/ (v_i, v_j) \in L \tag{62}$$

$$b_{ij}^{l} \leq MAXb_{ij} \qquad , \forall i, j \,/ (v_i, v_j) \in L \,, \;\; \forall l \in \{1 ... \lceil \log_2(N_g \cdot N_{gr}) \rceil \} \tag{63}$$

$$e_{ik}, s_{ijk}, t_{ik}, y_{ij}, P_{ik}^{OT}, P_{ik}^{LW} \geq 0, \; y_{ij}^{rg} \geq 0, \; \lambda_{ij}^{rg}, \mu_{ij}^{rg} \geq 0, \quad b_{ij}^{l}, \, MAXb_{ij} \; binaries \geq 0 \tag{64}$$

Notice that now, the range selection constraint is modified to equal a new binary variable $MAXb_{ij}$. When the latter is 1, the above model enforces the adjacency constraints in a similar way to Theorem 1 in Li et al. (2013) by means of considering equations $(60 - 61)$. However, seeking for an enhanced computational efficiency in our large-scale problem, we have introduced a crucial modification: we have reserved the all-zero Gray code –i.e. avoid its use to encode intervals- and enforced the implications $MAXb_{ij} = 0 \Rightarrow \lambda_{ij}^{rg} = \mu_{ij}^{rg} = 0 \Rightarrow g_{ij}^{rg} = 0$ with constraints $(56), (60), (61)$, (62) and (63).

For an example, consider that at the outset the binary variables are defined on the ranges listed formerly in Table 4. Hence, the seven definition intervals can be encoded as in Table 4, and the linear equations needed to incorporate the adjacency constraints on every connection $(v_i, v_j) \in L \;/\; i \neq 0, j \neq N+1$ are as follows:

$$\begin{array}{ll}
(a) & b_{ij}^{1} = (\lambda_{ij}^{r4} + \mu_{ij}^{r4}) + (\lambda_{ij}^{r5} + \mu_{ij}^{r5}) + (\lambda_{ij}^{r6} + \mu_{ij}^{r6}) + (\lambda_{ij}^{r7} + \mu_{ij}^{r7}) \\
(b) & b_{ij}^{2} = (\lambda_{ij}^{r2} + \mu_{ij}^{r2}) + (\lambda_{ij}^{r3} + \mu_{ij}^{r3}) + (\lambda_{ij}^{r4} + \mu_{ij}^{r4}) + (\lambda_{ij}^{r5} + \mu_{ij}^{r5}) \\
(c) & b_{ij}^{3} = (\lambda_{ij}^{r1} + \mu_{ij}^{r1}) + (\lambda_{ij}^{r2} + \mu_{ij}^{r2}) + (\lambda_{ij}^{r5} + \mu_{ij}^{r5}) + (\lambda_{ij}^{r6} + \mu_{ij}^{r6}) \\
(d) & MAXb_{ij} = (\lambda_{ij}^{r1} + \mu_{ij}^{r1}) + (\lambda_{ij}^{r2} + \mu_{ij}^{r2}) + (\lambda_{ij}^{r3} + \mu_{ij}^{r3}) + (\lambda_{ij}^{r4} + \mu_{ij}^{r4}) + \\
 & \qquad (\lambda_{ij}^{r5} + \mu_{ij}^{r5}) + (\lambda_{ij}^{r6} + \mu_{ij}^{r6}) + (\lambda_{ij}^{r7} + \mu_{ij}^{r7})
\end{array}$$

4.3. Heuristic for Approximate Resolution of MAUD Problems

After close examination of the models stated so-far, we have devised a computational procedure to get fairly good solutions to the hard MAUD problems in feasible times. It is a two-phase heuristics algorithm, built around the successive resolution of several auxiliary problems, all of them considering that the ranges which fully partition the feasible volume of total flow on each link are $p \in P^{g}$ (namely, that in which carriers presented their offers).

4.3.1. Phase1: Reducing the Available Real-Shipping Connections

First, we propose a way of choosing a subset of links $\hat{L} \subseteq L$ to be the only one where the discounts based on the volume are allowed. To this aim, we proceed as follows:

- Step1: Solve the continuous linear program resulting from minimizing the objective function:

$$
\begin{aligned}
F_1 = {} & \alpha \cdot \sum_{k\in K} \sum_{v_i \in V/C_{ik}>0} P_{ik}^{OT} + \beta \cdot \sum_{k\in K} \sum_{v_i \in V/C_{ik}>0} P_{ik}^{WL} + \gamma \cdot \sum_{v_i\in V} \sum_{k\in K} c_{ik}^{SOC} \cdot s_{i(N+1)k} \\
& + \quad \delta \cdot \sum_{k\in K} \sum_{v_i\in V} c_{ik}^{E} \cdot e_{ik} + \quad \eta \cdot \sum_{k\in K} \sum_{v_i\in V} c_{ik}^{T} \cdot t_{ik} \; + \\
& + \quad \varphi \cdot \sum_{(v_i,v_i)\in L} c_{ij}^{S} \cdot \sum_{p\in P^g} \sum_{g\in G} \left(F^{pg} \cdot z_{ij}^{pg} + DFA^{pg} \cdot y_{ij}^{pg}\right) \qquad (65)
\end{aligned}
$$

and only considering constraints $(2-10)$ –i.e. with no discounts at all. Let us denote the links with traffic assigned as $\cancel{L} \subseteq L$.

- Step2: Assuming a shape for the shipping costs like that in Figure 1 *(ii)*, we solve a simplified version of our planning problem, which considers the AUD problem as in $(1-16)$, but stated in the directed graph $\cancel{G} = (V, \cancel{L}, K)$. Once solved, we look up which links where assigned no zero flow values, and take them as the subset of links $\hat{\cancel{L}} \subseteq L$ to be passed to the next phase.

Finally, we make the following post-processing: We identify those links $\underline{L} \subseteq \hat{\cancel{L}}$ whose amount of assigned freight y_{ij}^{pg} is above the following value:

$$
B_{NoMAUD}^{pg} = \frac{L^{(p+1)g} \cdot (1 - DF^{(p+1)g})}{(1 - DF^{pg})} \qquad (66)
$$

We say that these are connections set at a 'bargain zone', to remark that we can proceed to over-declare the quantity shipped through them. Precisely, the convenience of generating alternative solutions which in MAUD metric should be better by just moving y_{ij}^{pg} towards the limit U^{pg} is what motivates Phase 2.

4.3.2. Phase2: Moving Traffic in Flat Towards Upper Bound

We improve the feasible solution arising from Phase 1 by means of a second auxiliary MILP model, which uses new symbols and variables:

Decision Variables:

δ_{ij}^{BARG}	1, if link $(v_i, v_j) \in L$ is being price according to bargain zone; 0 otherwise.
y_{ij}^{NORMpg}	Variable capturing the value of y_{ij}^{rg} when not in the bargain zone.
y_{ij}^{BARGpg}	Variable capturing the value of y_{ij}^{pg} when in the bargain zone.

We call this the 'Mix-MAUD model' and formally state it as follows:

$$F_3 = \alpha \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{OT} + \beta \cdot \sum_{k \in K} \sum_{v_i \in V / C_{ik} > 0} P_{ik}^{WL} + \gamma \cdot \sum_{v_i \in V} \sum_{k \in K} c_{ik}^{SOC} \cdot s_{i(N+1)k}$$

$$+ \delta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{E} \cdot e_{ik} + \eta \cdot \sum_{k \in K} \sum_{v_i \in V} c_{ik}^{T} \cdot t_{ik}$$

$$+ \varphi \cdot \sum_{(v_i, v_i) \in L} c_{ij}^{S} \cdot \sum_{p \in P^{g}} \sum_{g \in G} \left(y_{ij}^{pg} + \delta_{ij}^{BARG} \cdot B_{NoMAUD}^{pg} \right) \tag{67}$$

s.t.

$$(2 - 16)$$

$$y_{ij} = y_{ij}^{NORM} + y_{ij}^{BARG} \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in \underline{L} \tag{68}$$

$$y_{ij}^{BARG} \geq (B_{NoMAUD}^{pg} + 1) \cdot \delta_{ij}^{BARG} \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \tag{69}$$

$$y_{ij}^{BARG} \leq U^{pg} \cdot \delta_{ij}^{BARG} \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in \underline{L} \tag{70}$$

$$y_{ij}^{NORM} \leq B_{NoMAUD}^{pg} \cdot (1 - \delta_{ij}^{BARG}) \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in \underline{L} \tag{71}$$

$$\delta_{ij}^{BARG} \leq y_{ij} \quad , \forall i \neq 0, j \neq N+1 \,/\, (v_i, v_j) \in \underline{L} \tag{72}$$

$$y_{ij}^{NORMpg}, y_{ij}^{BARGpg} \geq 0, \qquad \delta_{ij}^{BARG} \; binary \geq 0 \tag{73}$$

5. CASE STUDY: THE ANDALUSIAN NETWORK OF CLINICAL LABORATORIES (ANCL)

Universal public health service networks requires of efficient laboratory test services (Plebani et al., 2006;Goswami, Singh, Chawla, Gupta, & Mallika, 2010). In the Andalusian autonomous region of southern Spain, these services are provided throughout the Andalusian Regional Network of Clinical Laboratories (ANCL), a large healthcare network with geographically dispersed hospitals, clinics, and testing laboratories.

The test services are an integrative part of diagnosis, therapy control and management for patients care, including risk screening in healthy patients. The process starts with collecting a biological sample from a patient at any laboratory within ANCL's extensive peripheral network. ANCL may test this specimen within its network or may outsource the analysis; we refer to this analysis as test processing or determination. After the processing laboratory has completed its clinical tests, it sends the results to the laboratory that collected the sample. Plebani et al. (2006) describe the sequence of tasks involved.

In early 2008, the regional authority appointed a multidisciplinary committee, including healthcare managers, clinicians and operations research engineers so as to conduct parallel work to understand the different attitudes and behaviors with respect to demand and capacity management prevalent within the ANCL, how these interact and how these compare to the organizational behaviors necessary to allow for improved performance. After studying comprehensive internal reports on ANCL’s prior activities in this area, the multidisciplinary committee reached two major action items. It would develop (1) a new reference model (i.e., paradigm), which would be based on a business process management (BPM) platform, to facilitate cooperation among laboratories and track tests within ANCL, and (2) a new planning procedure which throughout a centralized management of logistics aims to better utilize ANCL's laboratories and reduce the number of outsourced tests.

5.1. The New Business Perspective

A completely new business process (Contreras, 23Jun2012) was created focused on better managing the flow of tests within the ANCL, pursuing enhanced collaboration among members to cut down the outsourced tests while providing earlier results to patients. The key aspect was the interoperability among members, which happens when two or more actors communicate and collaborate – or interact- to achieve a common goal. The objective of this new perspective goes beyond the assurance of interoperability solely by communications specifications (standards like HL7, DICOM), to propose a new Healthcare Integration Platform (HIP).

The HIP is based on the Service Oriented Architecture (SOA) paradigm (Erl, 2008) in order to accomplish with scalability and efficiency requirements. The many Hospital Information Systems in use are integrated using the InterSystems Ensemble® seamless integration and development platform, implementing an Enterprise Service Bus (ESB) for the Andalusia Health Service. It is worth to remark that the HIP is reported in InterSystems' website as a success story – see http://www.intersystems.com/library/library-item/servicio-andaluz-de-salud-sas-base-their-hospital-soa-strategy-on-intersystems-ensemble/.

A new business process "Analytic Tests Module" has been implemented as a component of the HIP, aiming at the effective implementation of the recommendation concerning improved cooperation among ANCL members. On a whole, the implemented component supports querying, accessing and collecting information from the Information Laboratory Systems (ILS) at each member within the ANCL, when involved in the derivation of a clinical test order –namely, the clinical test has been directed to be executed in another lab-. Crucially, the precise track of derived tests has allowed the ANCL authorities to control the accomplishment of Service Level Agreements (SLA) among facilities.

5.2. ANCL Integrated Logistic Problem Definition

The method presented in this thesis has been applied to give rise to action (2), so that the decisions on coordination and improved logistics have been addressed throughout What-If analysis conducted using a DSS tool (Geographical Information Systems, Optimization Engine and Google Maps® API).

Next we present the features of the tool that is currently supporting the design decisions on the target network, helping managers in the quantitative analysis of the whole costs considering not only shipping costs but also operational costs due to product handling, overload and underutilization of facilities.

5.2.1. Background

The challenging ANCL planning problem is to find where to best satisfy the demand for clinical tests (i.e., process the clinical samples) and how to best route them within the distribution network, with the primary objective of minimizing operational costs: shipping costs, transshipment costs, processing and outsourcing costs, and additional operational costs when laboratories receive too few or too many samples to be analyzed.

Crucially, discounts on the shipping costs – i.e. price reduction depending on the quantity of freight committed- have been gained as a result of the centralized management of package carrier firm services that ANCL managers apply since 2009. Specifically, they use annual public tenders for which carrier firms bid: each carrier $g \in G$ bids presenting a single price offer for each shipping connection (i.e., offer the same set of discount ranges P^g for each link, with each range $p \in P^g$ characterized by a lower bound L^{rg}, an upper bound U^{rg}, and the discount rate DF^{rg}).

5.2.1.1. Related Work

Because the ANCL planning problem relates largely to the transportation between nodes (i.e., hospitals or clinical laboratories), we reviewed studies that address the perishable nature of goods and focused on the transportation stage. Andreatta and Lulli (2008) consider a real-world application of blood delivery from a blood bank to hospitals within a city; they model the problem as a multiperiod travelling salesman problem. Osvald and Stirn (2008) formulate a problem of perishable food distribution as a vehicle routing problem time window with time-dependent travel times. Ambrosino and Sciomachen (2007) determine the distribution plan for two products (fresh food and frozen food) to minimize the total travelling costs by formulating a vehicle routing problem with split delivery. These three works use a directed graph structure, which is also appropriate to represent the ANCL logistical issues. Nevertheless, they are not applicable to the ANCL problem, because they are suitable only for small networks and do not consider production decisions.

Henceforth, we take into account the above observations and concentrate in efficiently provide a tactical logistic plan for serving the forecasted demand. We model it as the distribution of some commodities (clinical samples) from the sources to the demand nodes, with transportation costs that exhibit the following complicating feature: each shipping connection will contribute to system-wide costs throughout a non-linear piecewise function of the flow along that connection –i.e. concave MCNFP-. Cohn, Davey, Schkade, Siegel, & Wong (2008) use a similar approach to deal with the cost reduction achieved by a package carrier firm when contracting with a cargo airline; they assume that the cargo airline presents a price offer to each client depending on the cost of the entire load purchased. However, in Cohn et al. (2008) discounts on shipments are a function of the overall flow of the network; in our case study, we use discount factors attached to the flow in each connection. Since each connection can be potentially allocated to a different carrier, the aggregated flow over commodities (total freight) on each connection acts as the discount driver. More specifically, the aggregated flow along that connection is priced according to a MAUD cost structure, which results from incorporating the bumping clause to the AUD scheme (Chan et al., 2002). Since capacity constraints appear both on facilities production and transportation, the model that arises is a Capacitated MCNFP with concave costs (CMCNFP-CC).

Next, we present the models developed to provide the framework for efficient operations in the target networks. Specifically, this means deciding on where to best satisfy the demand for commodities (i.e., destination facilities) and how to best route them within the distribution network, with the primary objective of minimizing operational costs: shipping costs, transshipment costs, processing and outsourcing costs, and additional operational costs when facilities workloads are too above or too beyond a certain reference workload. As claimed in (Andrade-

Pineda et al., 2013), the tradeoff between taking advantage of the volume-based price incentives in the transportation activity and minimizing the rest of operational costs arises as the key issue in addressing the ANCL annual logistics decisions.

5.3. The New Planning Procedure: Applying Our Method

We create a CMCNFP-CC model explained in a directed graph $\bar{G} = (\bar{V}, \bar{L}, K)$ representing the involved distribution network, with commodities set K (namely, the various clinical sample types travelling through the network), vertices set $\bar{V}$, links set $\bar{L}$, demands and installed capacities for each clinical test type at the vertices, and link capacities. In this model, the flow through a vertex incurs a processing cost (if the sample is analyzed) or a transshipment cost. Our model also includes costs for flowing along links, whether they represent shipping costs or outsourcing costs.

5.3.1. Graph Representation

To provide a flexible representation of the network, we identify the following functional entities:

- Serving center (SC): the clinical laboratory (vertex) that processes tests on samples; its main feature is its installed capacity.
- Outsourcing center (OC): a single entity that models the service points located outside the ANCL boundaries.
- Point of extraction (POE): the center that collects samples for analysis; it could be within ANCL (in an SC) or outside ANCL (in the OC).
- Demand transfer point (DTP): the center at which samples coming from POEs are collected (a process that involves reception, stabilization, and conservation); the samples are shipped later—typically to an SC.

We next represent ANCL by using a directed graph (see Figure 4), which contains N+2 vertices: N vertices represent the centers (i.e., SCs, POEs, DTPs), one artificial vertex represents the individual demand insertion point (i.e., the supersource vertex that supplies the total demand for the planning horizon) that feeds the POEs, and another artificial vertex represents the sink vertex for the outsourcing flows. For sample stability, if the distances between vertices are excessive (> 250 *km*), we exclude shipping connections.

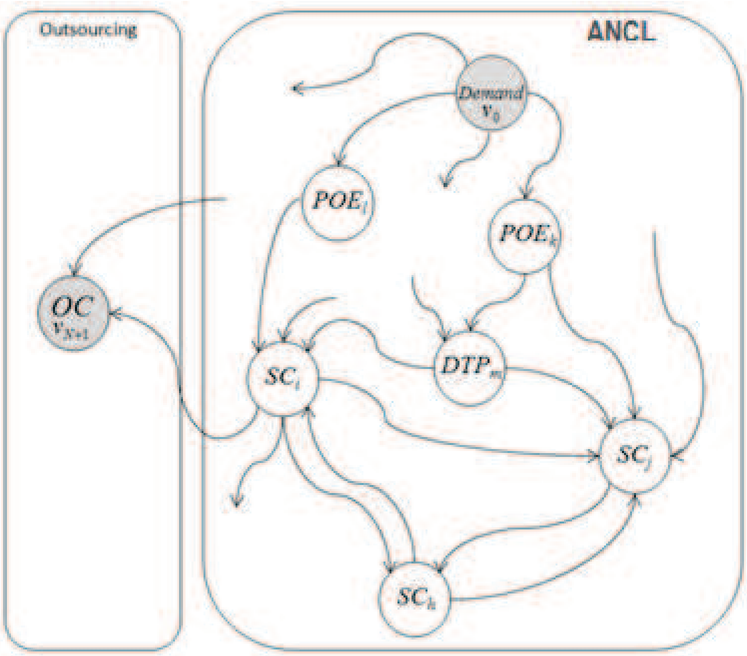


Figure 4 – This directed graph represents the regional network of clinical laboratories. Biological samples collected at points of extraction (POEs) are shipped to demand transfer points (DTPs) or service centers (SCs) for analysis, or to an outsourcing center (OC).

5.3.2. Evolving Shipping Costs and Solutions Approaches for the ANCL Planning Problem

At the outset, carriers requested sending commitment as a condition to offer increasing per-unit discount rates to be applied to price the whole freight committed in every connection. An AUD piecewise linear structure arises from the scale economies in the transportation activity, which requires a mixed integer formulation. Papers #1 and #2 consider the AUD costs problem.

In recent years, the ongoing competition among carriers and the centralized management of their services have allowed ANCL planners to avoid the sending commitment. Hence, the shipping costs follow a MAUD shape. Papers #3 and #4 address this MAUD costs problem.

5.4. Decision Support System for Supporting What-If Analysis

5.4.1. Requirements

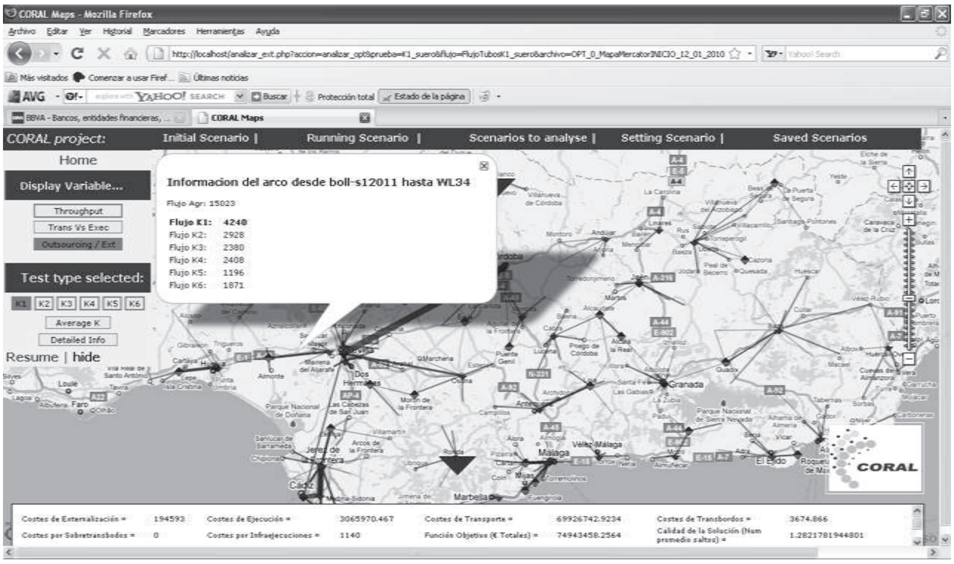
ANCL authorities needed comprehensive quantitative analyses to make informed decisions about efficiency improvements. Using decision tools to assess the alternatives for enhanced coordination and logistics in this large and complex network would be necessary. Specifically, because ANCL had opened new facilities as part of a general plan to improve access to medical care (Rodríguez Diaz 2011), planners needed a tool to respond to events in the changing ANCL environment; for example, a planner must consider that in setting up new hospitals, a hospital may come online (i.e., be activated) although its laboratory is still part of ANCL. The DSS had to be an IT tool that would address three requirements.

- It must be able to use input data from diverse sources to construct and resolve different scenarios, regardless of the amount of computer time needed.
- It must allow planners to analyze the workload and the flow assignments by studying a resolved scenario (i.e., annual plan) in greater detail.
- It must allow planners to compare scenarios. The tool must allow them to rank each potential plan based on the average expected satisfaction of patients, as if the potential plan had been in practice. Planners must be able to use the tool to make operating decisions on primary care, the ANCL service that drains the most resources.

5.4.2. The DSS Tool Developed

We coded the ANCL planning model in AMPL (Fourer, Gay, & Kernighan, 2003) to create a core computational application (i.e., optimization engine), which reads input data from a relational database that contains data collected from RNCL, computes the solution by resolving the large-scale MILP described in The ANCL Long-Term Planning section, and places the solution into the same database.

We packaged the optimization engine as a component of a Web-based DSS, which uses state-of-the-art IT tools to allow planners to revise input data, change parameter settings, run the planning model, and perform detailed analyses of the plans generated. We embedded an interactive graphical user interface (GUI) to facilitate these steps and allow the user to generate the appropriate ANCL annual production and transportation plan.



http://localhost/analizar_ext.php?accion=analizar_opt&prueba=K1_suero&flujo=FlujoTubosK1_suero&archivo=OPT_0_MapaMercatorINICIO_12_01_2010

Informacion del arco desde boll-s12011 hasta WL34

Flujo Agr: 15023

Flujo K1: 4240
Flujo K2: 2928
Flujo K3: 2380
Flujo K4: 2408
Flujo K5: 1196
Flujo K6: 1871

Costes de Externalización = 194593
Costes de Ejecución = 3065970.467
Costes de Transporte = 69926742.9234
Costes de Transbordos = 3674.866
Costes por Sobretransbodos = 0
Costes por Infraejecuciones = 1140
Función Objetivo (€ Totales) = 74943458.2564
Calidad de la Solución (Num promedio saltos) = 1.2821781944801

Figure 5 – The DSS provides a user-friendly interface based on the Google Maps API to allow a user explore a solution.

We coded the GUI using the PHP server-side scripting language, which allows planners to run the optimization engine and shows them a graphical representation of the output solutions based on the Google Maps API. The GUI allows the user to revise or modify the plan and to project and analyze What-If scenarios by changing data from the relational database to create new scenarios. The DSS provides user-friendly tools to enable the user to study a resolved scenario in greater detail and save it for future study or comparison, making it possible to compare two archived scenarios.

In addition to the Google Maps API standard functionalities (e.g., zoom, drag), our graphical representation of solutions is characterized by various icons (see Figure 5). It uses larger triangles (laboratories with higher values for the displayed decision variable) and thicker lines (links with heavy traffic for the displayed layer commodity k) for easier identification of issues. In addition, interactive access to a resolved scenario is possible by clicking on a specific laboratory (i.e., displaying its workload variable values) or by clicking on a specific link (i.e., displaying its flow variable values), as Figure 5 illustrates.

6. PAPERS RESULTS AND DISCUSSION

This chapter gives an overview of the main findings from the appended papers, describing the relation and connection between them and the research questions.

A quick glance at the result of each publication and its interpretation, starting at Paper#1 (Andrade-Pineda et al., 2013), is presented next.

6.1. The Road-map of ANCL Transformation

6.1.1. Paper #1: A DSS Tool around an Optimization Engine

The first result from (Andrade-Pineda et al., 2013) was a MILP model for addressing the integrated logistics annual decisions (an AUD formulation similar to that in chapter 3). Once the MILP is solved, the last step to fully specify the production and transportation plan is estimating the average geographical accessibility (AGA) indicator:

$$AGA = \sum_{k\in K} \Big[\sum_{(v_i,v_i)\in L} s_{ijk} + \sum_{v_i\in V} s_{i(N+1)k} \Big] \Big/ \sum_{k\in K} \sum_{v_i\in V} a_{ik} \tag{74}$$

, which indicates the average number of transshipments each test needs to reach the laboratory that will process the sample and hence, estimates the expected quality of service (QoS) provided.

The second result in this paper was a Web-based DSS tool that embeds the concerned optimization model and uses state-of-the-art IT tools to allow planners to revise input data, change parameter settings, run the logistic operational model, and perform detailed analyses of the plans generated, thereby fulfilling the quantitative analysis requirements dictated by ANCL authorities.

A sensitivity analysis based on design of experiments (DOE) (Montgomery, 2009) has been applied on the model arisen. As reported in (Andrade-Pineda et al., 2013), both DSS real-time usability and suitability to the ANCL plan are affected mainly by network size. Furthermore, the embedded model offers considerable flexibility to allow decision makers to implement a variety of policies because of the sensitivity of the expected QoS to the parameter settings.

6.1.2. The Process Changes

To great extent, the changes in any organization have to overcome the resistance of affected people. As reported in the seminal work (Andrade-Pineda et al., 2013), in order to take into account the ANCL personnel perspective, a multidisciplinary committee has guided the practical implementation of the new planning procedure for addressing the ANCL annual logistics decisions.

Since 2009 the DSS tool embedding our integrated logistics models has been used in the improvement of the primary healthcare service. Further, it has been unvaluable in guiding the transformation of this organization (for instance, in determining a schedule for the activation of the new facilities to be opened in planning the primary care service), as the generated production and transportation plans have performed progressively lower outsourcing and shipping costs and better access to testing services.

Similarly to the DSS tool, the HIP adoption was carefully prepared through a pilot project, focused also in the testing service on primary health care. Hence, in 2010 the Laboratory Component was tested with the purpose of defining the procedures and validating the workflow scheme.

By end 2011, there were a subset of 15 (out of 29) clinical laboratories that have fully adopted the new business perspective (HIP), serving 3.5 million people (corresponding to 464 primary care centers from a total of 1509). About 1440000 orders were derived in 2011 among them and electronically tracked within the HIP, the bill of outsourcing costs reduced in a 40% (from 1.45 M€ in 2010 to 900000€). Tracing the producing data, there were two main laboratories that have greatly increased their workload. They two are henceforth considered reference laboratories, providing the others with capabilities formerly purchased to external laboratories. Historical data by the end of 2011 indicate that the new operational model has led to cost containment while promoting the best use of fully-equipped facilities. Productivity bonuses (wages) have been paid to the efficient producing labs. As regards to ordering laboratories, they have taken advantage of the easier workflow to derive and track test orders (no paper, all in the HIP) and to get early test results to offer to patients (0.5-1 days in comparison with orders not tracked).

Further laboratories have followed in 2012 and 2013, to take advantage of progressively more attractive SLAs. In year 2013 all the members in the ANCL were in the HIP and on average a 9% of all orders were derived inside the ANCL. These changes have required the reorder of connections and dependencies among members in a dynamic pattern, to which planners have used the DSS tool.

6.2. Tractability Improvements

Over the years, major efforts have been done to improve the optimization engine at the core of the DSS. We first addressed how to best exploit the block structure of AUD problem. Later, the challenging MAUD problem that got in use made the tractability problem in the ANCL case study even more issuing – refer to Paper #4 for tractability reports on the real-sized arisen instances-.

Next we discuss our research results on improving the optimization engine in the core of the DSS tool. Some of them are contributions to general CMCNCF problems with concave costs, and other are case study contributions (e.g. enhanced responsiveness in coping with the ANCL annual planning problem in the DSS tool in use).

6.2.1. Paper #2: A GBD Algorithm on the AUD Problem

In Paper #2 two versions of the CMCNFP-CC problem are addressed: *(i)* A MILP model from which we derived a CBD procedure, and *(ii)* A MIBLP model which lead to a GBD one. We tried out the effective specialization of both decomposition approaches on the ANCL case study, in order to overcome the difficulties regarding to efficiency and speed-up of computations. Hence, we have incorporated certain enhancement strategies (LP preamble phase, MFS strategy, Dominant cuts generation, Dynamic RMP definition throughout deletion of inactive cuts) and test both Benders variants. In view of our computational experience the bilinear variant (GBD) outperforms the classical one (CBD).

Hence, Paper #2 converts the MILP model $(7-22)$ into a MIBLP, which is solved applying a GBD framework. In doing so, a binary RMP arises whose tighter formulation benefits the speed up of computations in two-fold: *(i)* Its relaxed resolution circumvents the difficulty of requiring plenty of computational time for solving the RMP (hard to solve to optimality as the number of iterations increase); while *(ii)* the successive lower bounds arising from the RMP remains a non-decreasing sequence.

Despite the insights gained on the practical application of variable decomposition, in our ANCL case study the results are not goods. Since the convergence times were up to 90 hours, we can conclude that this approach is not useful as regards as the responsiveness expected from the optimization engine as the core of their DSS.

6.2.2. Paper #3: Reformulation and Exact Approach to MAUD Problem

Our first contribution in Andrade-Pineda, Canca, & Gonzalez-R (2015) is a novel modeling technique that can be useful to gain computational efficiency in practical real-world problems effected by economies of scale with bumping clause. Our technique models the arisen MAUD functions as a composition of flat-ramp shapes. By taking the minimum of a fixed value (flat) resulting from over-declaring the quantity of freight committed and a load-dependent linear function (ramp), we accurately reflect the incurred transportation costs due to certain load while reducing the number of ranges.

Secondly, alternative formulations (MC, DCC, LogDCC) for the problem of interests are derived in this work. A test bed of 75 instances is used in order to evaluate the performance of the three approaches in comparison with the classical multiple choice approach in the extended range set (namely, without using our gadget). The MC approach outperforms the rest of analyzed approaches as well as the original model. It seems like if the interaction between the binary variables resulting from the MC linearization of MAUD with the rest of the model yield speed ups compared to the DCC and LogDCC approaches. Concerning the a priori promising logarithmic method stated in this work (LogDCC), it suffers some difficulties in solving large size ANCL problems. In that case, the amount of continuous variables and linear constraints added to substitute the original binary indicator variables causes a significant computational burden. This is shown in the numerical experiments, where, as illustrated, the DCC method improves the result of the logarithmic version.

6.2.3. Paper #4: Approximate Heuristic Approach to MAUD Problem

As reported in this paper, in the last years ANCL planners started the so-called 'anti-dispersion policy' that managers impose for simplicity in the control of the transportation activity, which consists on the requirement of activating less than a 40% of the total number of real shipping connections.

To great extent, the plans arisen from the heuristic method describe in chapter 4 emulate the effect of the novel anti-dispersion policy. Precisely, the main contribution of paper 4 is to speed up the output of feasible ANCL plans while adapting to this technical constraint. The approximate resolution procedure for the real-sized instances have enabled planners to obtain good solutions (less than a 4.5% to the optimum) in less than 1800 *s*.

6.3. The Contribution of This Thesis

The research work in this thesis has contributed to define the ANCL tactical logistics that has guided the transformation of this extensive healthcare network.

The layout of the network has been mapped into a directed graph, on which the involved planning problem has been modeled as a multi-commodity network flow problem with capacity constraints both on facilities production and transportation (CMCNFP). Focused on the definition of a framework for cost-efficient operations, our tactical planning procedure has incorporated realistic issues such that economies of scale that lead to concave routing costs, penalties due to overload and underutilization of facilities, inventory costs and outsourcing costs.

The optimization model providing this framework has been put into operation in a DSS to provide planners with the ability of conducting comprehensive quantitative analyses and hence, making informed decisions on the ANCL. Intending to improve the usefulness of this tool, we have studied several solutions strategies aiming at getting good solutions in quicker times. The different case study contributions are: *(i)* a deep analysis of a variable decomposition strategy from which insights are gained on the specialization methods of Benders Aproaches, greatly dependent of the specific real-life problem addressed, *(ii)* an heuristics proposal to get approximate resolution in shorter times and finally, *(iii)* a reformulation of the non-convex MILP using different linearization methods.

Beyond the ANCL case study, the main contribution of this thesis is the novel modeling approach based on the flat-ramp gadget to gain tractability in problems with economies of scale under the assumption of the bumping clause. A good understanding of the potential contribution of this modeling technique when applied jointly to different linearization methods to address CMCNCF problems with concave costs is provided by the extensive computational study in Andrade-Pineda, Canca, & Gonzalez-R (2015) –i.e. in Paper #3-. From it, we can conclude that the gadget is expected to positively affect in all the methods: as it is well known, the numbers of extra variables and constraints required in the linearization of the involved nonlinear function impact the performance of the arisen model.

7. CONCLUSIONS

As healthcare has gradually become a more privatized and contested sector, the development of new organizational changes to meet the opportunities for efficiency has lead healthcare networks to increase the complexity of the entire supply chain.

To great extent, the challenges in healthcare logistics turn around hospitals as the key elements in healthcare delivery networks. They implement a range of activities that notably include purchasing, inventory management and the distribution of supplies to the point of care. Many often, networks composed of geographically dispersed members address their logistics enhancements relying on Third-Party Logistics partners (3PL), refers to "the organizational practice of contracting-out part of or all logistics activities that were previously in-house" (Selviaridis & Spring, 2007). Through specialization, logistics service providers are assumed to have more expertise in performing logistics function than their customers.

7.1. Summing Up the Thesis

This thesis has studied the integrated logistics problem in healthcare networks, where very often planners encounter difficulties in the management of the logistics inter-dependencies between the different facilities. We have approached them as multi-site organizations which many often exhibit complementary production possibilities at several locations, with different kind of relationships (varying strength of linkages between the facilities and heterogeneous IT-Structures).

Drawing on the ANCL case study, it appears that the integration of the IT-Systems at the different facilities and locations within the network and the centralization of the logistic planning procedure can be of invaluable help for aligning operational models and organizational behavior around demand, capacity and network configuration. This suggests that although such integration projects are difficult, costly and complex, they seem worth undertaking.

7.2. Further Research Lines

We would like to conclude by pointing out future research lines.

The first one is again focused in the Tactical Planning problem in the target logistic network. We should deep in the possibilities of the Benders Decomposition when used joint to the gadget-based modeling approach. In order to circumvent the computational burden of Benders Algorithms in the ANCL problem, a promising approach is the one-tree Benders (Bai & Rubin, 2009; Botton, Fortz, Gouveia, & Poss, 2013; Fortz & Poss, 2009) which using the callback functions that modern commercial solvers provide avoids rebuilding the search tree at every iteration.

The second line consists on jumping to the Service Scheduling problem, thereby involving the time-based addition. In the ANCL case study, it should give rise to the logistical planning for the provision of different services to the primary care: specialized, critical, and emergency care. Depending on the type of service required, we could identify two primary delivery modes—express or regular mode (Andreatta and Lulli 2008). Express mode would be associated with urgent demands that must be met within 24 hours; regular mode (i.e., the remaining demands) could have a more flexible response time (typically two to four days). The inclusion of the time factor would compel us to use space-time network models (Cohn et al. 2007, Durbin and Hoffman 2008, Marín 2006, Marín and Codina 2008, Yan et al. 2006, Clark et al. 2004). We could load the ANCL routing problem with both urgent and regular requests, and determine which requests must be serviced immediately and which can be satisfied later.

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APPENDED PAPERS