Universidad Autónoma de Nuevo León

Facultad de Ingeniería Mecánica y Eléctrica

Subdirección de Estudios de Posgrado

Model for Integrated Supply Chain Analysis to Improve Decision Making

por

Adrian Mendoza Caballero

COMO REQUISITO PARA OBTENER EL GRADO

MAESTRÍA EN LOGÍSTICA Y CADENA DE SUMINISTRO

Octubre 2020

Universidad Autónoma de Nuevo León

Facultad de Ingeniería Mecánica y Eléctrica

Subdirección de Estudios de Posgrado

Model for Integrated Supply Chain Analysis to Improve Decision Making

por

Adrian Mendoza Caballero

COMO REQUISITO PARA OBTENER EL GRADO

maestría en logística y cadena de suministro

Octubre 2020

UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN   FACULTAD DE INGENIERÍA MECÁNICA Y ELÉCTRICA

Universidad Autónoma de Nuevo León
Facultad de Ingeniería Mecánica y Eléctrica
Subdirección de Estudios de Posgrado

Los miembros del Comité de Tesis recomendamos que la Tesis Model for Integrated Supply Chain to Improve Decision Making, realizada por el alumno Adrian Mendoza Caballero, con número de matrícula 1985761, sea aceptada para su defensa como requisito para obtener el grado de Maestría en Logística y Cadena de Suministro

El Comité de Tesis

Dr. Rodolfo Garza Morales
Asesor

MLyCS Fátima Sanchez Ruíz
Revisor

José Daniel mosquera Artamonov

Dr. José Daniel Mosquera Artamonov
Revisor

Vo. Bo.

Dr. Simón Martínez Martínez
Subdirector de Esudios de Posgrado

FIME

153

San Nicolás de los Garza, Nuevo León, octubre 2020

Contents

List of Figures

List of Tables

ACKNOWLEDGEMENTS

"You think you're the painter, but you're the canvas"

- John Green

To all the people that loved me into this moment. **Thank You**

Resumen

Adrian Mendoza Caballero.

Candidato para obtener el grado de Maestría en Logística y Cadena de Suministro con orientación en Diseño y Análisis.

Universidad Autónoma de Nuevo León.

Facultad de Ingeniería Mecánica y Eléctrica.

Título del estudio: MODEL FOR INTEGRATED SUPPLY CHAIN ANALYSIS TO IMPROVE DECISION MAKING.

Número de páginas: 44.

OBJETIVOS Y MÉTODO DE ESTUDIO: El objetivo de esta investigación es presentar una metodología para la optimización integrada de la cadena de suministro, los modelo de programación entera mixta están pensados como una forma de mejorar el proceso de toma de decisiones para aumentar la eficiencia de las operaciones comerciales en la gestión de la cadena de suministro.

CONTRIBUCIONES Y CONLUSIONES: Se presentan los resultados de dos modelos para la integración de la cadena de suministro utilizando el modelo de descomposición de Benders para mejorar el tiempo de resolución de los modelos.

Firma del asesor: ______________________________
Dr. Rodolfo Garza Morales

Chapter 1

Introduction

1.1 Introduction

There are two main factors that can lead to inefficiencies observed in supply chains, first, the chain design itself may be inefficient and secondly, undesired performance could result from biases or poor decision making (Steckel, Gupta, Banerji, 2004). The decision maker in a supply chain can have a huge impact in the future and profitability of a company, therefore professionals in the field of logistics and supply chain management should use every tool available in order to diminish risk and to make sure their organization is operating in the best possible way.

By making better decisions in day to day operations a company is able to produce value for their customers, especially when they are able to successfully align their logistics strategy with their long-term business strategy. Decisions in supply chains become too complex for professionals and researchers when they cannot identify relevant points through the uncertainty of the situations and often fail to find better alternatives to the problems they constantly face. (Liu, Leat, Moizer, Megicks, Kasturiratne, 2013). Successful supply chain management requires correct decision making from upper management related to the ability of handling vast numbers of data points associated with manufacturing, logistics, transportation, inventory management, etc. A successful supply chain professional must be able to balance transportation, warehousing space, inventory management, delivery times and demand for all customers in order to maintain competitiveness in a global market, however with so many variables it is often difficult to find the correct strategy for a company.

Traditionally, professionals and researchers of supply chains, analyze the individual stages within the larger chain, but current research has found a need for a more integrated approach to logistics and supply chain design (Beamon, 2007).

It is important to understand that the ultimate goal in supply chain planning is to generate value and improve profitability, however implementing changes is not always simple since there are many factors to consider, changes involve coordination of a lot of workers in order to effectively modify day to day operations, therefore a detailed analysis must be done in order to understand where changes might be more effective in the entire network, always keeping in mind that the company's job is to satisfy customer's needs. The operations in supply chain and logistics are considered in today´s economy vital tools for businesses to remain competitive (Wang, Lai, Shi, 2011).

1.1.1 Problem Statement

There is an increasingly persistent problem in logistics and supply chain management today, which affects both small and big companies. This is due to the fact that despite having a large amount of resources available and research in the field of supply chain and logistics, most organizations make their decisions individually and in a compartmentalized fashion, meaning that they make the best decision available for each of their departments attempting to improve the overall performance of their organization, however research has shown that this is not the case.

Companies operate this way because when a supply chain has a large number of departments or components it can be very difficult to coordinate them and to have a comprehensive understanding of how exactly it is that their company is currently operating. When you have large amounts of constantly changing data it can be extremely difficult to make a decision that increases the effectiveness and efficiency of a company as a whole.

It is necessary in this current economic climate, that new operating strategies are implemented making use of the technological resources that we currently have available, among them, mathematical models and computational software that allows us to process large amounts of data to support better decision making processes.

One of the reasons for these type of models not to be widely implemented in the day-to-day operations of companies is that, first of all, there a generalized lack of knowledge of how to transform daily operations into observable and measurable data, which can be transformed into more manageable information which can provide greater clarity regarding operations and performance.

Secondly, even if a company has the necessary knowledge and resources to apply this type of solutions, in order to build a comprehensive model that takes into account all the relevant parts that make up a supply chain, the processing time of the data can be extremely high, which affects the feasibility of implementation for different companies, that is because it is not practical for organizations to wait a long time for a solution while dealing with the day to day operation.

For companies to operate effectively, the supply chain needs to be treated as a whole cohesive unit, a holistic approach to optimization must be taken. By optimizing a supply chain as a single element and by using mathematical techniques to reduce the implementation time, companies can increase their revenue and decrease money and time waste. Despite the fact that there are many tools available to supply chain professionals, currently most people rely today on tools like Excel spreadsheets or empirical knowledge acquired through time to run the operations of a company.

There is a risk factor associated to making major changes to how a company operates, adjusting operational policies within a company can result for example, in the accumulation of excess inventory at some point as well as lack of inventory for a manufacturing process or inability to meet demand at the point of consumption.

The main trend in supply chain management has been driven by competitive pressures and relates to the improvement of efficiencies enabled by advances in information technology applied to cost control (Chen Samroengraja, 2004). The focus of a company is to increase value in order to improve profitability in the long term, companies may relinquish market share and potential revenues because of poor cost management or lacking of an adequate value generation strategy (Brunnermeier Martin, 2002).

Measuring the total logistical cost improves the financial performance of the supply chain, allowing companies to make decisions with a broader vision. A proper measurement provides information for better implementation of strategies on the flow of materials and associated information in each link (Bhagwat Sharma, 2007).

1.1.2 HYPOTHESIS

By analyzing a supply chain from an integrated point of view, that is, considering it as a series of highly related business processes, professionals of supply chain management can improve their decision-making process that will result in a positive impact on the efficiency of their operations.

1.1.3 OBJECTIVE

The objective of this research is to present a model for integrated supply chain optimization considering several parts of a supply chain and optimize them as a single unit. The proposed multi-period mixed integer linear programming model is intended as a way to improve the decision-making process in order to increase the efficiency of business operations in supply chain management.

1.1.4 JUSTIFICATION

It is well known by researchers in the operations research field that the sum of the optimal solutions to the parts is not the optimal solution of the whole.

1.1.5 THESIS STRUCTURE

This research project is comprised of a total of six chapters. The first chapter includes an introduction that includes the objective of this research, hypothesis, and justification, as well a description of the methodology used.

The second chapter details with the theoretical background that is required for this research, this includes a general description of a supply chain and its components, the costs associated with managing a supply chain, optimization models and decomposition techniques used in logistics management.

The third chapter described in detail the methodology used, including the literature review for this project, the different mathematical models and techniques used to support this research as well as the experimentation used.

Chapter number four describes in detail the models and the results obtained. Chapter number five describes the data analysis as well as the conclusions of this research project.

CHAPTER 2

ANTECEDENTS

2.1 INTRODUCTION

The main goal in the manufacturing industry is to create wealth by adding value to customers and selling products. Every manufacturing company controls the flow of materials from different suppliers and through different processes add value before a product reaches their final customers, we need to understand however, that supply chain management extends beyond the physical movement of materials from one end to the other, it involves purchasing , manufacturing , planning , distribution , customer service , etc. Therefore, we can understand the supply chain as a connected series of activities concerned with planning, coordination and control of different raw materials and transforming them into finished goods.

Supply chain is not just a group of stages involved to satisfy a customer request, but rather a network of interrelated stages involved to do customer requests. We want to manage this network's flow and also find the best network structure or supply chain design to maximize the beneficially (Geunes Pardalos, 2003). A large numbers of manufacturing models have been proposed for the design and planning supply chain network (Mo et al., 2005). The selection of partners in the supply chain network management is important because supply chain management really needs the inter cooperation of the partners at the upstream, midstream, and downstream echelons along the supply chain (Wang, 2009).

One of methods for studying an issue is modeling. Modeling different aspects can be investigated without any limit, which means that no change is needed to be made on the real-world system. Among different types of modeling, mathematical modeling is the main one in studying various aspects in this under review field. Any mathematical modeling consists of four important parts, parameters, variables, objective function(s), and constraints. By objective function(s) and constraints model developer demonstrates goals of developing a model and also boundaries it faces.

Fundamentally, every supply chain planning and scheduling problem is at heart an optimization problem. Its solution involves determining the best way to synchronize supply and demand across the supply chain network – to boost customer satisfaction and bottom-line results. There are two main factors that can lead to inefficiencies observed in supply chains, first, the chain design itself may be inefficient and secondly, undesired performance could result from biases or poor decision making (Steckel, Gupta, Banerji, 2004). In every company there is a person who is responsible for the decision-making process in supply chain, the decisions this person makes can have a huge impact in the future and profitability of a company. Professionals in the field of logistics and supply chain should use every tool available in order to diminish risk and to make sure their organization is operating in the best possible way.

A successful supply chain professional must be able to balance transportation, warehousing space, inventory management, delivery times and demand for all customers in order to maintain competitiveness in a global market, however with so many variables it is often difficult to find the correct strategy for a company.

Despite the fact that there are many tools available to improve decision-making, currently most people today rely on tools like Excel spreadsheets or empirical knowledge acquired through time to run the supply chain of a company, the thought process behind it is, if this is the way that it has been done in the past, then this is the way that we should continue doing it. There is often a lot of resistance to change the way a company operates because they are not able to analyze the supply chain to prevent unwanted consequences. Major changes in the supply chain policy within a company can result for example, in the accumulation of excess inventory at some point as well as lack of inventory for a manufacturing process or inability to meet demand at the point of consumption.

It is important to understand that the ultimate goal in supply chain planning is to generate value and improve profitability, however implementing changes is not always simple since there are many factors to consider, changes involve coordination of a lot of workers in order to effectively modify day to day operations, therefore a detailed analysis must be done in order to understand where changes might be more effective in the entire network, always keeping in mind that the company's job is to satisfy customer's needs. The operations in supply chain and logistics are considered in today´s economy vital tools for businesses to remain competitive (Wang, Lai, Shi, 2011).

2.2 SUPPLY CHAIN COSTS

The main trend in supply chain management has been driven by competitive pressures and relates to the improvement of efficiencies enabled by advances in information technology applied for cost control (Chen Samroengraja, 2004). The focus of a company is to increase value in order to improve profitability in the long term, companies may relinquish market share and potential revenues to competing producers because of poor cost management or lacking of an adequate value generation strategy.(Brunnermeier Martin, 2002). Measuring the total logistical cost improves the financial performance of the supply chain, allowing to make decisions with a broader vision, its proper measurement provides information for better implementation of strategies on the flow of materials and associated information in each link.

(Bhagwat Sharma, 2007). Typically, costs in supply chain are broken down as follows:

2.2.1 Procurement Costs

Procurement refers to the process of acquiring goods that enable a company to operate by transforming or reselling these goods to their customers. This is one of the first costs any company faces, the amount of money needed in order to obtain raw materials or a finished product from another company is referred to as procurement costs, administrative and invoicing expenses are also considered (Winston, 1987) , other factors might include the amount of space used in a warehouse or the amount of time spent by workers in processing different purchasing orders. There are several mathematical models that might help with this decision making for the optimal way of purchasing raw materials or finished products from a different company.

2.2.2 Transportation Costs

Transportation costs refers to the expenses involved in moving one product from their place of origin to their destination, which is often the final customer. “Because transportation costs historically have been less than 10 percent of total expenses, management has paid little attention to extracting savings through judicious routing of shipments” (Winston Albright, 1997). One of the most important fields of supply chain and logistics management is transportation network, there are numerous benefits to improvement transportation operations as it offers great potential for costs reduction and customer service improvement .(Icle, 2006)

Transportation costs are closely related to procurement cost because they are impacted by the volume of product that a company purchases from a supplier, additionally there are factors to consider like whether a company owns its own fleet or if shipping needs to be outsourced to a 3PL company.

2.2.3 Inventory Costs

Inventory refers to the products that a company keeps on a warehouse before they can be transformed by a manufacturing or purchasing process in order to be delivered to a customer. The importance of inventory cost management comes from balancing supply with demand, protect against uncertainties in demand, and act as a buffer between the critical parts of the supply chain (Lambert, Stock, Ellram, 1998). Inventory expenses often take shape, for example, by the rent that a company must pay for the warehouse that houses their products or by the money they must pay workers in order to move the product around within their building.

Additionally a company must face several costs that are hidden and therefore difficult to consider for operations planning, these hidden costs include lost, damaged or stolen products as well as products that might become obsolete because they have to stay on the warehouse for too long and have to be discarded.

2.2.4 Manufacturing Costs

Manufacturing costs are the costs needed to transform raw materials into a finished product by a manufacturing process. There are mainly three factors that go into manufacturing costs, the cost of the raw material involved in the production, the wages of the workers that are involved in the manufacturing process as well as the cost of the machines required to transform a product, other factors to consider might be overtime paid to workers in demand increases or the maintenance needed to keep a machine going for a long period of time.

Similarly, to inventory cost, in manufacturing there often hidden costs that need to be considered, these include the utilities paid for the factory, taxes paid for machinery, parts and supplies for maintenance as well as the depreciation of the company's assets.

2.3 Production Sequencing

During a manufacturing process is not often possible or cost effective to go from any one product to another, in order to produce an item, different processes might be needed in order to clean and prep a machine, the costs related to these processes are often referred to as set-up costs. Many optimization problems that focus on manufacturing in supply chain are too complex to solve by conventional optimization techniques because of sequencing restrictions (Udhayakumar Kumanan, 2010).

If the person in charge of production planning uses a computational tool to generate the production scheduled for a manufacturing plant, the optimal solution might dictate to go from one product to another without taking into consideration how long it takes to get a machine ready after manufacturing the previous item, this is why companies often make use of a production sequencing wheel that dictates the order in which all products must be produced given the limitations of the manufacturing equipment.

There have been several papers in operations research to study how sequencing flexibility increases performance in a manufacturing environment, flexibility in this context refers to the number of alternative sequences in which the operations can be performed (Joseph Sridharan, 2011). In supply chain planning, when the use of mathematical models for production planning in real-world environments is considered, production sequencing must be included in the restrictions of the models to obtain results that can be applied in a real production situation.

2.4 Decomposition Techniques in Optimization Models

There is one problem that arises from analyzing the supply chain as a cohesive unit rather that from a separate approach and that is the amount of variables in each model, which requires a great amount of computational power and time to be solved which can make it difficult for models like these to be used in real life situations outside of an academic point of view. A tool that can be used to minimize this is the usage of a decomposition algorithm for linear programming models which would reduce the solution time required. decomposition techniques that can be used in trying to solve a linear programming problem, this research uses the Benders decomposition algorithm to reduce the solution time for the replenishment policy model. Benders decomposition is an algorithm in linear programming used to solve large linear programming problems having a special block structure. This technique is named after Jacques F. Benders.

2.4.1 Benders Decomposition Algorithm

The main objective in Benders decomposition is to separate the problem into two sets of variables, mainly integer and continuous, although the technique can be used to solve linear programming problems that can be solved by another faster technique like network flow programming as will be showed late. The master problem is solved to fix the integer variables, and subproblems solve for continuous variables. When the subproblems are solved, the dual variable is used to generate Benders cuts that eliminate infeasible solutions. These cuts are added to the master problem and the procedure repeats itself through an iteration process until the value of an arbitrarily chosen fixed gap is close enough to find an optimal solution. Conejo et. al (2004) explain the Benders algorithm for mixed integer linear programming problems as follows:

$$minimize\ \sum_{i=1}^{n} c_i x_i + \sum_{j=1}^{m} d_j y_j$$

Subject to:

$$\sum_{i=1}^{n} a_{li} x_i + \sum_{j=1}^{m} e_{lj} y_j = b_l\ ; \qquad l = 1, \ldots, q$$

$$x_i^{down} \leq x_i \leq x_i^{up}, \quad x_i \in N; \qquad i = 1, ..., n$$

$$y_j^{down} \leq y_j \leq y_j^{up}, \quad y_i \in R; \qquad j = 1, ..., n$$

- Step 0: Set the iteration counter to $\nu = 1$ and solve the following master problem:

$$minimize\ \sum_{i=1}^{n} c_i x_i + \alpha$$

Subject to:

$$x_i^{down} \leq x_i \leq x_i^{up}, \quad x_i \in N; \qquad i = 1, ..., n$$

$$\alpha \geq \alpha^{down}$$

- Step 1: Solve the linear programming subproblem:

$$minimize\ \sum_{j=1}^{m} d_j y_j$$

Subject to:

$$\sum_{j=1}^{m} e_{lj} y_j = b_l - \sum_{i=1}^{n} a_{li} x_i \ ; \qquad l = 1, \ldots, q$$

$$y_j^{down} \leq y_j \leq y_j^{up}, \quad y_i \in R; \qquad j = 1, ..., m$$

$$x_i = x_i^{(\nu)} \ : \ \lambda_i; \qquad i = 1, \ldots, n$$

The solution to this problem is $y_1^{(\nu)}$, ... , $y_m^{(\nu)}$ with the dual variables $\lambda_1^{(\nu)}$**, ... ,** $\lambda_n^{(\nu)}$.

- Step 2: Compare the upper and lower bounds of the objective function of the original problem:

$$z_{up}^{(\nu)} = \sum_{i=1}^{n} c_i x_i^{(\nu)} + \sum_{j=1}^{m} d_j y_j^{(\nu)}$$

$$z_{down}^{(\nu)} = \sum_{i=1}^{n} c_i x_i^{(\nu)} + \alpha^{(\nu)}$$

If the value of $z_{up}^{(\nu)}$ - $z_{down}^{(\nu)}$ is smaller than the value of a pre-specified tolerance then the optimal solution is $x_1^{(\nu)}$, ... , $x_n^{(\nu)}$ and $y_1^{(\nu)}$, ... , $y_m^{(\nu)}$. In the case of CPLEX studio the default value for this tolerance is $1x10^{-6}$. If the value is not smaller than the tolerance the algorithm continues.

- Step 3: Update the iteration count to $\nu = \nu + 1$ and solve the master problem:

$$minimize \ \sum_{i=1}^{n} c_i x_i + \alpha$$

Subject to:

$$\alpha \geq \sum_{j=1}^{m} d_j y_j^{(k)} + \sum_{i=1}^{n} \lambda_i^{(k)} \left(x_i - x_i^{(k)} \right); \qquad k = 1, ..., \nu - 1$$

$$x_i^{down} \leq x_i \leq x_i^{up}, \ \ x_i \in N; \qquad\qquad i = 1, ..., n$$

$$\alpha \geq \alpha^{down}$$

The solution to the problem is $x_1^{(\nu)}$, ... , $x_n^{(\nu)}$ and $\alpha^{(\nu)}$. Then step 1 is implemented again.

2.5 LITERATURE REVIEW

Several authors have tried to analyze the supply chain as a single unit in the past however some of the resulting models become too complex, therefore requiring a long computing time to solve, making them difficult to implement in real-world scenarios. One way to mitigate this problem is to use a decomposition algorithm to help reduce the solution time by dividing the model is smaller pieces that are easier to solve. There have been a number of papers that have apply these types of algorithms to supply chain problems, in particular the Benders decomposition algorithm, however most of them focus on just one process of the supply chain, this research will implement several links of a supply chain to be optimized as a single entity.

In the past decades there have been several applications of mixed integer linear programming using the Benders decomposition algorithm in supply chain analysis. These applications cover all aspects of research and design on supply chain for both deterministic and stochastic problems.

Supply Chains for the most part have been managed and studied as a series of distinct, compartmentalized business processes; this can be noticed by studying the papers on table 1 where very few of them deals with more than one process. Currently, however, customers' expectations are higher than ever, they demand more customization from products they purchase, as well as high quality and low delivery times, meeting these demands is now considered for a company as the next great opportunity for competitive advantage (Stewart, 1997).

It is important for decision makers in supply chain to understand that while making strategic decisions for a company, several variables such as demands and costs, may change dramatically from decision time to implementation time which may complicate operations and make it seem like the wrong decision was taken (Z. J. M. Shen, 2007). When you add the compartmentalization of traditional supply chain design it becomes extremely difficult to implement a long-term business strategy.

As has been noted before, there are major cost factors associated with managing a supply chain, these costs are highly related and should be considered jointly when designing a supply chain. Building a support system that integrates these costs can be immensely challenging for companies, however it is a big opportunity to develop an strategy that could generate a competitive advantage in the marketplace (Z. M. Shen, Daskin, Shen, & Daskin, 2005).

Several authors have published papers in recent years showing the need to study a supply chain as an integrated unit. Ryu et al. in 2007 proposed a multiperiod model for operational policies. Timpe et al. in 2000 developed a mixed-integer linear programming model for the chemical industry that covered all major aspects of supply chain management of a multi-site network.

Varma et al. in 2007 researched the impact of enterprise-wide coordination on a company´s performance and sustainability, focusing on the integration of strategic and tactical decision-making processes, concluding that "strategic finance and operations research communities should form the basis for research in large-scale enterprise-wide modeling and optimization"

Sundaramoorthy et al. in 2006 proposed a model for the problem of resource allocation and planning in multistage and multiproduct pharmaceutical batch plants, considering campaign changeovers, key resources, maintenance and safety stock as a decision support tool in the pharmaceutical industry.

Bok et al. in 2000 proposed a mixed integer linear programming model for multiperiod planning, considering purchasing, distribution and inventory restrictions, because of the size of the model the authors then use a decomposition algorithm for solving the problem reducing the solution time. You and Grossmann in 2010 developed a model for multi-echelon supply chain and inventory management with uncertain demand however, this was modeled as a non-linear programming problem.

Jayaraman and Pirkul (2001) developed an integrated logistics model for locating production and distribution facilities to support strategic and operational decisions, the problem is a mixed integer linear programming model.

Table 1 shows different authors that have used benders decomposition in different facets of supply chain optimization to reduce the solution time of large-scale mixed integer linear programming problems. These research papers have been categorized into planning, logistics, transportation, scheduling, inventory, and design to represent the main area of supply chain that was optimized with the decomposition algorithm.

Authors	Planning	Logistics	Transportation	Scheduling	Inventory	Design
Adulyasak et al. (2015)			X			
Behnamian (2014)	X					
Boland et al. (2016)		X				
Boschetti et al. (2009)				X		
Botton et al. (2013)						X
Canto (2008)				X		
Cordeau et al. (2006)						X
Cordeau et al. (2001)				X		
Corréa et al. (2007)			X			
Fortz et al. (2009)						X
Gelareh et al. (2015)			X			
Jiang et al. (2009)		X				
Laporte et al. (1994)			X			
Luong (2015)	X					
Oliveira et al. (2014)	X					
Osman et al. (2014					X	
Pishvaee et al. (2014)						X
Saharidis et al. (2011)	X					

Tabla 2.1: Applications of Benders Algorithm in supply chain

Chapter 3

Methodology

3.1 Methodology

As was previously discussed the objective of this work is to develop an integrated supply chain model that shows how the decision-making process for professionals can be improved by studying a supply chain as a series of highly interconnected processes rather than an independent and compartamentalized unit. To develop this research project the first step was to do a thorough literature review, first looking for authors that have used mathematical optimization models inside supply chain management problems, then they were analyzed to understand which part of the supply chain they are addressing.

All the papers that were consulted were then categorized individually to have a better understanding of the current state of logistics and supply chain research. The next step was to look for authors and research papers that analyze a supply chain as a whole cohesive unit, to have a better understanding of the impact this type of optimization had on different corporations and the way they operate. Additionally,papers in which decomposition algorithms were used to improve the solution time of each particular problem were studied in order to choose a mathematical tool to be used in this research.

Once all the information had been gathered the next step was to define the research scope to correctly set the expectations and parameters of the different problems that will be addressed later. This includes which companies will be analyzed as well as identifying which links of the supply chain that are optimized in each case. This step is considered deeply important to have a clear understanding of the data that needs to be gathered as well as to get an expectation of the results that it will be obtained. Next all three mathematical models were developed with the information provided from upper management personnel that worked closely with this research to validate the nature of their operations as well as the data that needs to be supplied in order for this models to properly work.

All the specific data that was gathered from these companies has been modified for confidentiality reasons, nevertheless they reflect the way the companies operate and later new data can be supplied to reflect the current state of each company and to help him optimize the operations in each supply chain.

Once older models were developed and all the data was gathered the next step was to run different instances of each model and to collect the resulting data including the solution time in order to properly graph how each model behaves.

Finally with all the data available the last step is to analyze it in order to understand the results want to be able to give each company a specific recommendations in terms of the way they operate how best to achieve optimal status.

3.2 Research Scope

It is important to define the scope of this research in order to properly identify the areas of supply chain that are being optimized while supporting a better decision-making process. There are three mathematical models based on two different companies each with their own individual problems. Model number one focuses mainly on the procurement of raw materials for a company with a manufacturing plant in

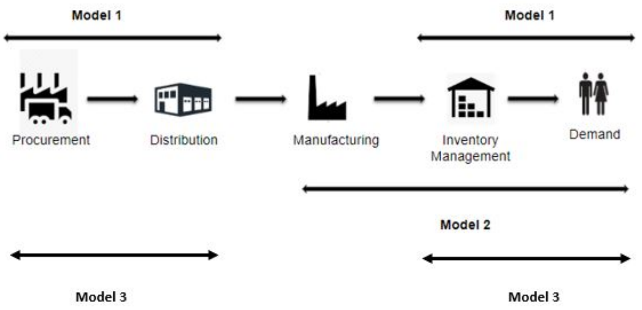

Figura 3.1: Research Scope

Monterrey Mexico, the company has consolidation centers in Asia where materials from different suppliers can be consolidated and then sent to the manufacturing plant where it is kept in inventory in the warehouse or supply production.

The second model is based on a glass manufacturing company that operates under production sequencing restrictions. The production is scheduled under a known demand and the end product is kept on inventory or sent to the customers depending on the demand for a given time period.

The third models focuses on determining first were to install a new manufacturing plant and then to reorganize their distribution network in order to meet a known demand from customers allowing to keep inventory for each item.

Diagram 1 shows the areas of the supply chain that are optimized in each model, based on this diagram it is possible to see that the areas in the scope of this research are procurement, distribution, production scheduling and inventory management.

3.3 Mathematical Models

There are two models that were developed for this research, one of them deals with the procurement, inventory management and distribution process of a company that

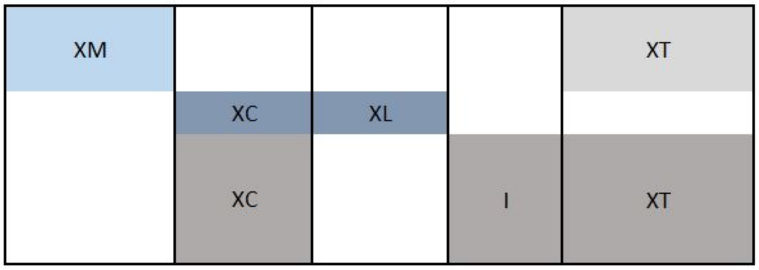

Figura 3.2: Structure Model 1

uses consolidation centers to reduce help reduce the number of shipments from their suppliers.

These models will be solved on CPLEX Optimization Studio first using the default branch and cut algorithm and then the Benders algorithm to see how much the computing time can be reduced by breaking the main model into one or more subproblems. The results will be analyzed to check for the feasibility of implementation in a real-world work environment.

The first models seeks to minimize the distribution as well as the inventory costs to satisfy a deterministic demand for each item shipped directly from the supplier or through a consolidation center. Figure 3.2 shows the structure of this model, whe XM represents the variable for direct shipment from the supplier, XC and XL are the variables for shipping items trough the consolidation center, I represents the inventory and XT the number of pallets for each item.

The second model focuses of production scheduling with sequencing restrictions as well as inventory management and the distribution process to a network of clients with known demand for their products, this mixed integer linear programming model will be solved both by the branch and cut and Benders algorithm.

3.4 Solution Software

In order to solve the linear programming problem that has been introduced, CPLEX optimization studio will be used. The default solution algorithm for CPLEX Optimization Studio is branch and cut, an algorithm that uses cutting planes to branch and bound. However, the latest version of the software offers an integrated Benders decomposition option where the software automatically assigns all integer variables to the master problem and the rest to the subproblem or it allows the user to manually assign the variables to each subproblem.

3.5 Results

The results for both problems are presented for different instances including the number of variables and restrictions used, the production scheduling and shipping schedules for both problems as well as the amount of inventory for each time period. The total computing time for both the branch and cut algorithm as well as Benders will be presented.

3.6 Data Analysis

Once the raw data from the solutions is obtained, they will be analyzed to see how feasible it is to implement a similar strategy in a real-world scenario. The computing time is especially important to analyze due to the fact that if the problem grows too complex and it takes a long time to be solved by the computer it would be impractical to use for any supply chain professional.

CHAPTER 4

RESULTS

4.1 MODEL 1

Assumptions:

- The number of suppliers, consolidation centers and distribution centers are known.
- The demand for each item is known.
- There are two types of containers used for shipping (10 and 20 feet).
- The items can be shipped directly to the distribution center or through the consolidation centers.
- The inventory costs for each item are known.
- The consolidation centers do not hold inventory, the items are shipped to Mexico within the same time period.

  Sets:

  P : Set of suppliers

  B : Set of consolidation centers

S : Set of items

E : Set of containers

T : Set of time periods

Parameters:

CD_{ep} : Cost of shipping a pallet using container e directly from the supplier p.

CC_{spb} : Cost of shipping a pallet of item s from supplier p to consolidation center b.

CM_{eb} : Cost of shipping of a container e from consolidation center b to the distribution center

CI_s : Inventory costs at the consolidation center for item s

Q_e : Capacity of container e

d_{st} : Demand for item s for period t

Variables:

XM_{ept} : Number of containers e shipped from supplier p during period t.

XC_{spbt} : Number of pallets shipped of item s from supplier p from consolidation center b during period t.

XL_{ebt} : Number of containers e shipped from consolidation center b to the distribution center during period t.

I_{st} : Number of pallets from item s in inventory during period t.

XT_{spt} : Number of pallets of item s shipped directly to the distribution center from supplier p during period t.

Model:

$$Min\ Z = \sum_{e=1}^{E}\sum_{p=1}^{P}\sum_{t=1}^{T} CD_{ep}XM_{ept} + \sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{t=1}^{T} CC_{spb}XC_{spbt} + \sum_{e=2}^{E}\sum_{b=1}^{B}\sum_{t=1}^{T} CM_{eb}XL_{ebt}$$
$$+ \sum_{s=1}^{S}\sum_{t=1}^{T} (k-1)\,(\ CI_s)\, I_{stk}$$

Subject to:

$$\sum_{s=1}^{S} XT_{spt} - \sum_{e=1}^{E} Q_e XM_{ept} \leq 0 \quad \forall p, t$$

$$\sum_{s=1}^{S}\sum_{p=1}^{P} XC_{spbt} \ - \sum_{e=1}^{E} Q_e XL_{ebt} \leq 0 \quad \forall b, t$$

$$\sum_{p=1}^{P} XT_{spt} + \sum_{p=1}^{P}\sum_{b=1}^{B} XC_{spbt} + I_{s(t-1)} - I_{st} = d_{st} \quad \forall s, t$$

$$XM_{ept},\ XL_{ebt}\ Z$$

$$XC_{spbt},\ I_{stk},\ \ XT_{spt} \geq 0$$

Where equation (1) is the objective function that minimizes the sum of direct shipping costs from the supplier, shipping costs to the consolidation centers, shipping costs to the distribution center and inventory costs. Equation (2) ensures the number of pallets shipped directly to the distribution center does not exceed the capacity of the containers. Equation (3) ensures that the number of pallets shipped from the consolidation centers does not exceed the capacity of the containers. Equation (4) ensures that the demands for each item is met either from shipments or inventory at the distribution center. Equations (5) and (6) are logical constraints.

4.2 Results Model 1

For each step of the experimentation the number of SKUs and suppliers were incremented gruadually to measure how they affected the solution time, this caused the models to increase in their complexity which is presented in terms of the number of variables and constraints for each model.

Products	**Plants**	**Variables**	**Constraints**
500	5	300.000	36.005
600	6	432.000	50.406
700	7	588.000	67.207
800	8	768.000	86.408
900	9	972.000	108.009
1000	10	1.200.000	132.010
1100	11	1.452.000	158.411
1200	12	1.728.000	187.212
1300	13	2.028.000	218.413
1400	14	2.352.000	252.014
1500	15	2.700.000	288.015

Tabla 4.1: Variables and Constraints Model 1

As it can be seen the experimentations grew larger each time resulting in a high number of variables and constraints for each experimentation. The largest experimentation for this research problem had almos ten million variables and 26 thousend contraints, however using the benders decomposition algorithm the solution time was kept under control.

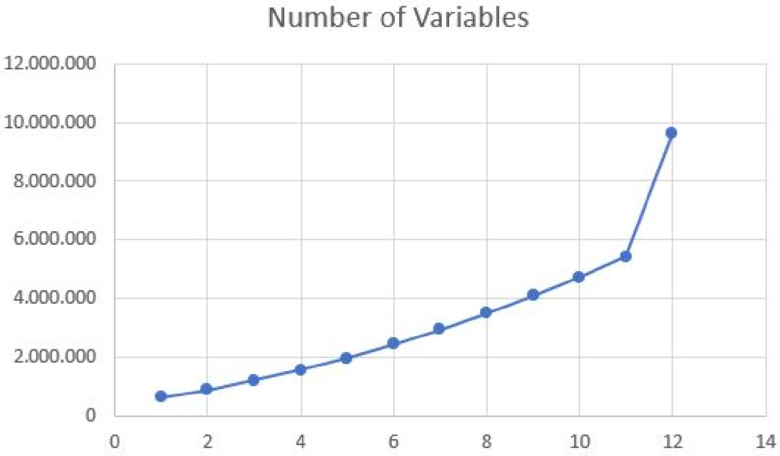

Figura 4.1: Varibles Model 1

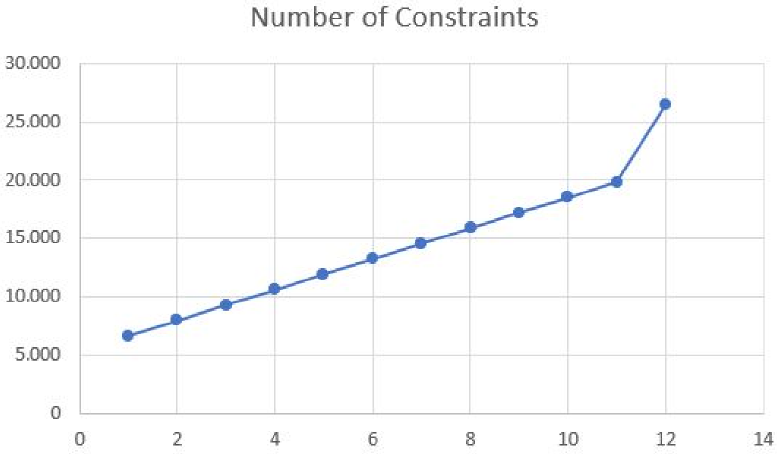

Figura 4.2: Constraints Model 1

Products	**Plants**	**B&C**	**Benders**
500	5	00:35:07	00:21:18
600	6	00.48:39	00:29:03
700	7	01:14:11	00:39:40
800	8	01:21:09	00:51:30
900	9	01:52:13	01:08:32
1000	10	02:23:29	01:33:33
1100	11	02:56:35	01:56:30
1200	12	04:37:33	02:51:14
1300	13	05:09:17	04:32:24
1400	14	06:15:21	04:51:14
1500	15	07:57:30	04:37:47
2000	200	18:13:44	10:53:21

Tabla 4.2: Branch and Cut vs Benders

Figure 4.1 and 4.2 shows how the number of variables and constraints grew as the experimentation process went on, increasing in complexity every time until it reached almost 10 million variables.

Table 4.2 shows the difference in the computing time for each of the experimentation steps between the CPLEX solution time using the default algorithm which is Branch and Cut for this specific software versus the Benders decomposition algorithm.

Finally figure 4.3 is a graph for the computational times for each of the experimentation steps that are described in table 4.2.

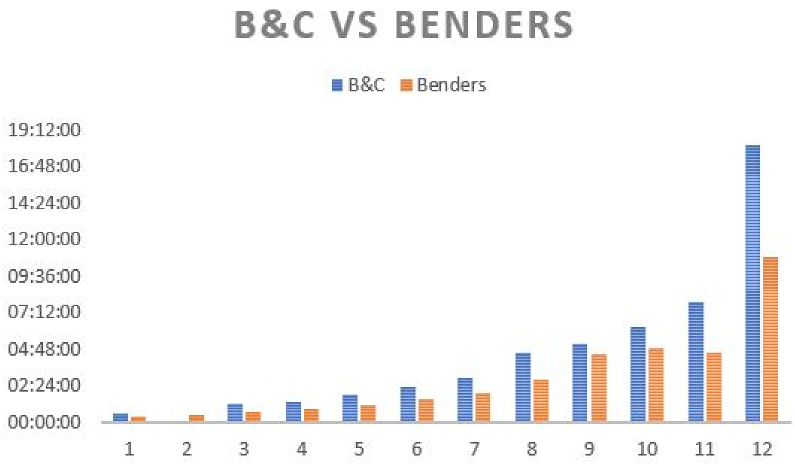

Figura 4.3: BC vs Benders

4.3 Model 2

Assumptions:

- The setup costs for each item are known.
- The demand for each item is known.
- There number of clients is known
- The efficiency of each plant is measured by products manufactured each hour.
- The inventory costs for each item are known.
- The capacity for each plant is known and constant.

Sets:

P : Set of products

F : Set of manufacturing plants

C : Set of customers

O : Set of ovens

T : Set of time periods

Parameters:

VP_p : Selling price for each product p

$CS_{p'pt}$: Setup cost changing from product p´ to p during time period t.

M_{pf} : Manufacturing cost of product p manufactured at plant f

CI_{pf} : Inventory costs for product p at factory f

CT_p : Transportation cost of product p

d_{pct} : Demand for product p by customer c during period t

CA_f : Production capacity of factory f.

ST_{pof} : Setup time for product p in oven o at factory f.

TF_{ft} : Available time at factory f at time t.

Variables:

YS_{fopt} : Binary variable to decide to include setup cost from transitioning from product *p´to p* in factory f during time period *t.*

XC_{pfct} : Number of units sold of product p from factory f to customer c during time period *t.*

XP_{pft} : Number of units produced for product p in factory f during time period

t.

I_{pft} : Number of units from item p in inventory in factory f during period t.

XT_{pfct} : Number of units of item p from factory f shipped to customer c during time period t.

Model:

$$Max\ Z = \sum_{p=1}^{P}\sum_{c=1}^{C}\sum_{t=1}^{T} VP_pXC_{pct} - \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{o=1}^{O}\sum_{l=1}^{L}\sum_{t=1}^{T} M_{pf}XP_{pfolt} - \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{c=1}^{C}\sum_{t=1}^{T} CT_{fc}XT_{pfct}$$

$$-\sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{t=1}^{T} CI_pI_{pft} - \sum_{f=1}^{F}\sum_{o=1}^{O}\sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=1}^{T} CS_{folpp}YS_{folppt}$$

Subject to:

$$\sum_{p=1}^{P}\sum_{o=1}^{O}\sum_{t=1}^{T} XP_{pfot}\,\frac{1}{e_{pfo}} + \sum_{p=1}^{P}\sum_{o=1}^{O} ST_{pf} \leq \sum_{t=1}^{T} TF_{ft} \qquad \forall f$$

$$\sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{t=1}^{T} XP_{pft} + \sum_{p=1}^{p}\sum_{f=1}^{F}\sum_{c=1}^{C}\sum_{t=1}^{T} XT_{pfct} - \sum_{p=1}^{P}\sum_{t=1}^{T-1}\sum_{k=t+1}^{T} I_{pftk} + \sum_{p=1}^{P}\sum_{t=1}^{T-1}\sum_{k=t+1}^{T} I_{pftt} \leq d_{pct} \quad \forall p,t$$

$$\sum_{p=1}^{P} XP_{pfot} \quad \leq MYS_{fot}\ \forall f,o,t$$

Where equation (1) is the objective function that maximizes the sum of the total items sold. Equation (2) ensures the quantity of items manufactured does not exceed the capacity of each plant. Equation (3) ensures that the manufacturing time and setup time for each plant does not exceed the available time. Equation (4) ensures that the demands for each item is met either from shipments or inventory at the distribution center.

4.4 RESULTS MODEL 2

For each step of the experimentation the number of SKUs and plants were incremented gradually while the number of ovens and manufacturing lines remained constant to measure how they affected the solution time, this caused the models to increase in their complexity which is presented in terms of the number of variables and constraints for each model.

Products	**Plants**	**Variables**	**Restricciones**
500	5	300.000	36.005
600	6	432.000	50.406
700	7	588.000	67.207
800	8	768.000	86.408
900	9	972.000	108.009
1000	10	1.200.000	132.010
1100	11	1.452.000	158.411
1200	12	1.728.000	187.212
1300	13	2.028.000	218.413
1400	14	2.352.000	252.014
1500	15	2.700.000	288.015

TABLA 4.3: Variables and Constraints Model 2

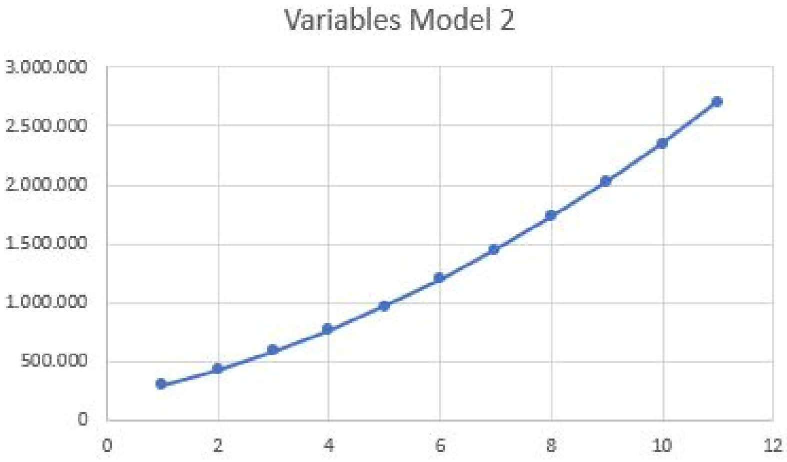

Figura 4.4: Variables Model 2

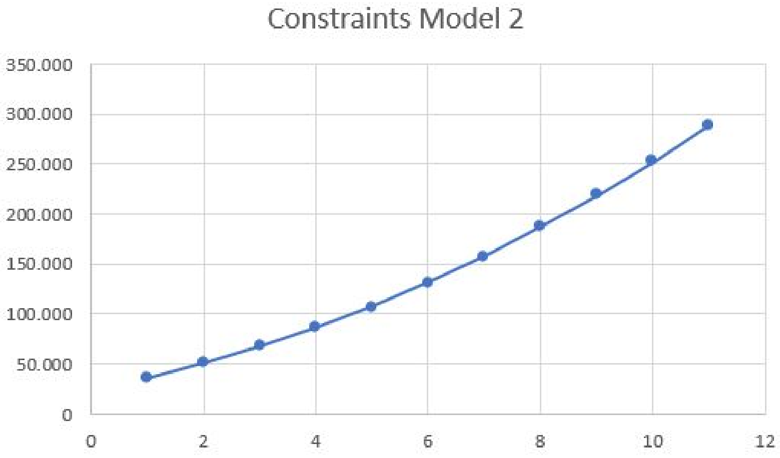

Figura 4.5: Constraints Model 2

Products	**Plants**	**B&C**	**Benders**
500	5	11:19:34	08:20:12
600	6	13:23:18	10:09:54
700	7	15:27:02	11:59:36
800	8	19:30:46	12:49:18
900	9	21:34:30	15:23:00
1000	10	23:38:14	17:28:42
1100	11	27:14:52	19:11:26
1200	12	26:23:11	22:03:32
1300	13	31:23:12	22:57:48
1400	14	36:24:12	23:14:17
1500	15	34:42:38	23:53:32

Tabla 4.4: B&C vs Benders Model 2

Figure 4.4 and 4.5 show how the experimentation process increased the complexity of the model increased reaching almost 3 million variables at the end.

Finally table 4.4 and 4.6 show how the solution time using the Benders decomposition algorithm was reduced compared to the regular Branch and Cut algorithm used by the CPLEX solution software.

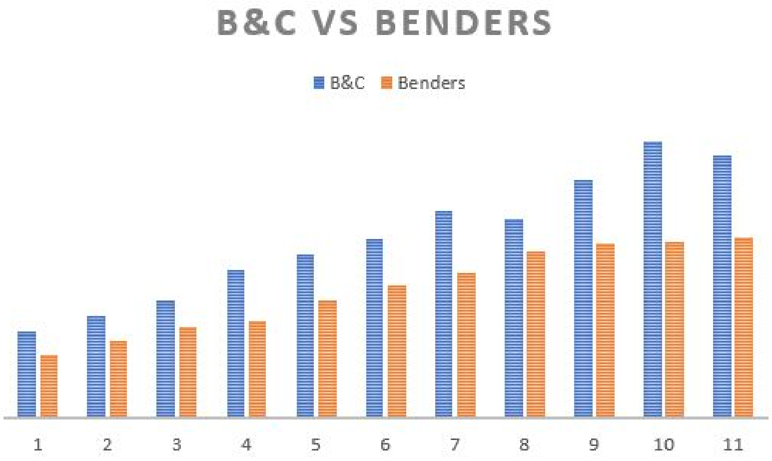

Figura 4.6: B&C vs Benders Model 2

CHAPTER 5

DATA ANALYSIS AND CONCLUSIONS

Once all the data was gathered during the experimentation process, including the solution time for each model and the number of variables and constraints of each model, an analysis was performed in order to understand how each of the two models behaved and to be able to reach a conclusion to the project.

5.1 ANALYSIS

One thing that is worth mentioning regarding this research project, is the fact that the results of the experimentation varied slightly in both instances because of the structure of each model, for the first model, the solution time showed a better reduction than the second model given the imbedded network structure of the constraints, this allowed the decomposition algorithm to perform more efficiently in the first set of equations as it was shown in the previous chapter.

For the second model the solution time also was reduced, using the same decomposition technique however it did not perform as well as the first one because of the structure and the complexity of the problem.

It is also important to note, that the number of variables for both models as well as the constraints was extremely high, this complicated the solution time in both cases, as for example, in the first model the number of variables reached almost 10 million, this was expected as it was stated in the hypothesis as one of the complications to expect when solving more than one stage of a supply chain and treating it as a single unit.

The solution time in both models was acceptable given the initial parameters established by each company, which were able to keep within a manageable timeframe as it never exceeded 30 minutes for each step of the experimentation process.

One thing that is worth noting, is the fact that a powerful computer is also required to efficiently solve these problems, as a regular laptop struggled to perform the last experimentation steps, however most companies use standard commercially available equipment, therefore and of the main takeaways, is also the necessity of computational equipment capable of handling these types of models.

The experimentation process shows that it is possible to treat the different stages of a supply chain within the same model with the objective to optimize them, but there are factors that need to be considered when applying this methodology in a real-world scenario, including properly identifying all the costs involved, being able to identify the relevant links within the supply chain in order to increase the value offered to customers.

5.2 CONCLUSIONS

Mathematical models are quantitative tools that can be very useful in terms of decision making within supply chain operations and can be used in a large number of processes to include different stages in the supply chains of companies which can help provide the end customer with more value while reducing operating costs.

During the development of this project it was evident that despite the complexity of modeling different tasks in the supply chain in a single mathematical model due to the number of variables and equations, for a supply chain professional or a researcher it is very useful to treat the supply chain as a single unit in order to its global optimum, thus improving the operations.

A person familiar with these types of models, can have a broad competitive advantage over other companies in the logistics environment while treating several stages of the supply chain as one unit. It helps to give a better vision to the operational strategy and for decision making in the short, medium and long term.

In general, it can be concluded that the solution tool proposed for both companies was successfully implemented by helping with a supply strategy, inventory management and distribution in relation to the costs obtained in each of the models.

5.3 Future Work

To continue with this research project in the future, other decomposition techniques such as column generation for larger problems can be explored, different types of cuts such as Lagrangian cuts could be used to solve the master problem and subproblems.

Additionally, these decomposition techniques can be compared with heuristic methods to solve complex mathematical optimization problems.

CHAPTER 6

BIBLIOGRAPHY

Adulyasak, Y. , Cordeau, J.-F. , & Jans, R. (2015). Benders decomposition for production d routing under demand uncertainty. Operations Research, 63 (4), 851–867 .

Argyropoulou, M., Sharma, M. K., Bhagwat, R., Lazarides, T., Koufopoulos, D. N., & Ioannou, G. (2010). Measuring supply chain performance in SMES. *Handbook on Business Information Systems*, *19*(3), 699–715.

Bhagwat, R., & Sharma, M. K. (2007). *Performance measurement of supply chain management: A balanced scorecard approach. 53*, 43–62.

Bok, J.-K., Grossmann, I. E., & Park, S.(2000). Supply chain optimization in continuous flexible process networks. Industrial & Engineering Chemistry Research, 39(5), 1279–1290

Boyd, S., Xiao, L., Mutapcic, A., & Mattingley, J. (2007). Notes on Decomposition Methods. *Notes*, *D*(2006), 1–36. Retrieved from

Brunnermeier, S. B., & Martin, S. A. (2002). Interoperability costs in the US automotive supply chain. *Supply Chain Management*, *7*(2), 71–82.

Chen, F., & Samroengraja, R. (2004). Order volatility and supply chain costs.

Operations Research, *52*(5). https://doi.org/10.1287/opre.1040.0132

George B. Dantzig, P. W. (1960). *Decomposition Principle for Linear Programs.*

Icle, R. A. R. T. (2006). *A genetic algorithm for two-stage transportation problem using priority-based encoding.* *354*(17510138), 337–354. https://doi.org/10.1007/s00291-005-0029-9

Jayaraman, V., & Pirkul, H. (2001). Planning and coordination of production and distribution facilities for multiple commodities. European Journal of Operational Research, 133(2), 394–408

Joseph, O. A., & Sridharan, R. (2011). *Effects of routing flexibility , sequencing flexibility and scheduling decision rules on the performance of a flexible manufacturing system.* 291–306. https://doi.org/10.1007/s00170-011-3158-0

Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management. *Industrial Marketing Management*, *29*(1), 65–83. https://doi.org/10.1016/S0019-8501(99)00113-3

Lambert, D. M., Stock, J., & Ellram, L. (1998). *Fundamentasl of Logistics Management*. Irwin/McGraw-Hill.

Liu, S., Leat, M., Moizer, J., Megicks, P., & Kasturiratne, D. (2013). A decision-focused knowledge management framework to support collaborative decision making for lean supply chain management. *International Journal of Production Research*, *51*(7), 2123–2137. https://doi.org/10.1080/00207543.2012.709646

Rahmaniani, R., Crainic, T. G., Gendreau, M., & Rei, W. (2017). The Benders decomposition algorithm: A literature review. *European Journal of Operational Research*, *259*(3), 801–817. https://doi.org/10.1016/j.ejor.2016.12.005

Ryu, J., & Pistikopoulos, E. N.(2007). Multiperiod planning of enterprise-wide supply chains using an operation policy. Industrial & Engineering Chemistry

Research,

46(24), 8058–8065

Serdarasan, S. (2013). A review of supply chain complexity drivers. *Computers and Industrial Engineering*, *66*(3), 533–540. https://doi.org/10.1016/j.cie.2012.12.008

Shen, Z. J. M. (2007). Integrated supply chain design models: A survey and future research directions. *Journal of Industrial and Management Optimization*, *3*(1), 1–27. https://doi.org/10.3934/jimo.2007.3.1

Shen, Z. M., Daskin, M. S., Shen, Z. M., & Daskin, M. S. (2005). *Trade-offs Between Customer Service and Cost in Integrated Supply Chain Design.* (June 2014). https://doi.org/10.1287/msom.1050.0083

Steckel, J. H., Gupta, S., & Banerji, A. (2004). Supply chain decision making: Will shorter cycle times and shared point-of-sale information necessarily help? *Management Science*, *50*(4), 458–464. https://doi.org/10.1287/mnsc.1030.0169

Sundaramoorthy, A., Xianming, S., Karimi, I.A., & Srinivasan, R. Presented in PSE2006,July 09–13.An integrated model for planning in global chemical supply chains

Timpe, C. H., & Kallrath, J. (2000). Optimal planning in large multi-site production networks. European Journal of Operational Research, 126(2), 422–435.

Udhayakumar, P., & Kumanan, S. (2010). *Sequencing and scheduling of job and tool in a flexible manufacturing system using ant colony optimization algorithm.* 1075–1084. https://doi.org/10.1007/s00170-010-2583-9

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems*, *51*(2), 262–269. https://doi.org/10.1016/j.dss.2010.11.020

Winston, W. (1987). *Investigacion de operaciones: Aplicaciones y Algoritmos*

Winston (p. 663). p. 663.

Winston, W., & Albright, C. (1997). *Practical Management Science*. South - Western.

You, F., & Grossmann, I. E.(2010). Integrated multi-echelon supply chain design with inventories under uncertainty: MINLP models, computational strategies. AIChE Journal, 56(2), 419–440

RESUMEN AUTOBIOGRÁFICO

Adrian Mendoza Caballero

Candidato para obtener el grado de
Maestría en Logística y Cadena de Suministro
con orientación en Diseño y Análisis

Universidad Autónoma de Nuevo León
Facultad de Ingeniería Mecánica y Eléctrica

Tesis:

MODEL FOR INTEGRATED SUPPLY CHAIN ANALYSIS TO IMPROVE DECISION MAKING

Egresado de la carrera de ingeniería industrial por parte de la Universidad Autónoma Metropolitana, cuenta con 3 años de experiencia en el área de manejo de inventarios y abastecimiento. Trabajó como Greenlight Coordinator para Uber y como jefe de inventarios para Bostik México. Actualmente es estudiante de tiempo completo en la Maestría en Logística y Cadena de Suministro.