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AN APPROACH FOR THE INTEGRATION OF INTELLIGENT MAINTENANCE SYSTEMS AND COLLABORATIVE DECENTRALIZED SPARE PARTS SUPPLY CHAINS

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Esta Dissertação foi julgada adequada para obtenção do Título de "Mestre em Engenharia de Produção", e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia de Produção.

Florianópolis, 9 de Fevereiro de 2017.

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Este trabalho é dedicado à minha família, que acompanha minha caminhada a qualquer distância.

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Coming together is a beginning.
Keeping together is progress.
Working together is success.

(Henry Ford)

RESUMO

As cadeias de suprimento de peças de reposição são particularmente desafiadas pela baixa previsibilidade da demanda, necessidade de altos níveis de serviço e custo de estoque. Para lidar com esses desafios, através de uma estratégia de sincronização dos participantes de cadeias de suprimentos, o planejamento colaborativo pode ser combinado aos sistemas inteligentes de manutenção que auxiliam na predição das falhas. Porém, modelos hierárquicos de integração têm pouca aceitação dos atores da cadeia, que não desejam compartilhar dados estratégicos. Modelos descentralizados promovem a viabilidade do planejamento colaborativo, entretanto ainda não foram aplicados em cadeias de suprimentos de peças de reposição. Neste contexto, no presente trabalho, uma análise bibliométrica com revisão bibliográfica sobre colaboração e planejamento da cadeia de suprimentos é aplicada com o intuito de verificar os principais conceitos, direções e oportunidades de pesquisa. Foram identificadas lacunas na aplicação de modelos descentralizados em casos reais, bem como uma falta de suporte para a escolha de métodos de resolução. Dessa forma, o objetivo desse trabalho é propor um procedimento estruturado para embasar a aplicação de planejamento colaborativo descentralizado em cadeias de suprimentos de peças de reposição. Para isso, uma tabela de características é construída com o intuito de apoiar a escolha do método de resolução de problemas lineares. Na sequência, é desenvolvido e testado um procedimento estruturado para adequar um conceito de planejamento colaborativo decentralizado a cadeias de suprimentos de peças de reposição integradas a sistemas inteligentes de manutenção. Esse procedimento estruturado desenvolvido é aplicado em um caso teste e como resultado um modelo adequado de planejamento operacional colaborativo é proposto para o aprimoramento dessa cadeia de suprimento. O planejamento descentralizado obteve melhores resultados que uma abordagem clássica de gestão mesmo em cenários de alta variação na demanda, como ocorre nas cadeias de suprimentos de peças de reposição.

Palavras-chave: Gestão da Cadeia de Suprimentos, Planejamento da Cadeia de Suprimentos, Colaboração, Peças de Reposição, Manutenção, Pesquisa Operacional.

ABSTRACT

Spare parts supply chains are particularly challenged by the low predictability of the demand, the need for high service levels and the cost of inventory. To address these challenges through a strategy of synchronizing supply chain participants, collaborative planning can be combined with intelligent maintenance systems that help predict failures. However, hierarchical models of integration have little acceptance from actors in the chain, who do not wish to share strategic data. Decentralized models promote the feasibility of collaborative planning but have not yet been applied in spare parts supply chains. In this context, in the present work, a bibliometric analysis with a bibliographic review on collaboration and supply chain planning is applied in order to verify the main concepts, directions and research opportunities. Research opportunities were identified in the application of decentralized models in real cases, and there was a general lack of information to support the choice of a solving method. Thus, the objective of this work is to propose a structured procedure to support the application of decentralized collaborative planning in supply chains of spare parts. For this, a table of characteristics is constructed to support the choice of the method for solving linear problems. A structured procedure is then developed and tested to tailor a decentralized collaborative planning concept to a spare parts supply chain integrated with intelligent maintenance systems. This developed structured procedure is applied in a test case and, as a result, an adequate model of collaborative operational planning is proposed for the improvement of this supply chain. Decentralized planning was identified as having achieved better results than a classical management approach even in scenarios of high demand variation, such as in spare parts supply chains.

Keywords: Supply Chain Management, Supply Chain Planning, Collaboration, Spare Parts, Maintenance, Operations Research

UMA ABORDAGEM PARA A INTEGRAÇÃO DE SISTEMAS DE MANUTENÇÃO INTELIGENTES E CADEIAS DE SUPRIMENTOS DE PEÇAS DE REPOSIÇÃO COLABORATIVAS DESCENTRALIZADAS

INTRODUÇÃO

Máquinas e equipamentos utilizados na indústria estão sujeitos a degradação causadas por diversos fatores. Tal degradação necessita ser reparada com agilidade, buscando evitar pausas ou gargalos na produção.

Dentro das estratégias de manutenção existentes, pode-se destacar a manutenção preditiva, onde um monitoramento contínuo é realizado em peças críticas para avaliar seu desempenho, possibilitando a previsão de falha ou necessidade de troca da mesma. Tal estratégia de manutenção é possibilitada pelo atual estado da microeletrônica e *software*, que permite definição de parâmetros a serem monitorados e uma boa antecipação de demanda por uma peça de reposição.

A cadeia de suprimentos tem sua complexidade elevada no caso das peças de reposição. Os métodos de previsão de demanda são ineficientes devido ao padrão errático das falhas. Dessa forma, o uso dos sistemas inteligentes de manutenção pode potencializar o eficiente planejamento da cadeia de suprimentos através da antecipação da demanda possibilitada pelo monitoramento das condições das peças.

Ainda que possível encontrar um modelo para o planejamento de cadeias de suprimentos de peças de reposição integradas a sistemas inteligentes de manutenção na literatura, é inexistente a existência de um modelo para esse caso considerando a inexistência de uma hierarquia entre os atores presentes na cadeia de suprimentos de peças de reposição, o que pode tornar o modelo pouco aceitável por parte das organizações que compõem a cadeia, devido à necessidade de compartilhamento de informação nem sempre desejada.

OBJETIVOS

O objetivo geral deste trabalho é propor um procedimento estruturado para basear uma aplicação eficiente do planejamento da cadeia de suprimentos descentralizada colaborativa para a cadeia de fornecimento de peças sobressalentes integrada a sistemas de manutenção inteligentes.

Os objetivos específicos deste trabalho são:

• Identificar tendências e oportunidades de pesquisa na área;

• Elevar características que ajudem na escolha do método de resolução do método de modelagem mais utilizado para a otimização de cadeias de abastecimento descentralizadas;
• Elaborar um modelo de simulação para analisar os resultados fornecidos pelo modelo de otimização e sua desempenho estocástica;
• Implementar em um caso de teste os modelos matemáticos e de simulação construídos.

METODOLOGIA

Para atingir os resultados desejados, a pesquisa foi dividida em três etapas.

Primeiramente, uma revisão bibliométrica e sistemática da literatura foram executadas com o objetivo de identificar as principais tendências e oportunidades na área.

Posteriormente, uma revisão de métodos foi aplicada para construir uma tabela que dê base na escolha do método de resolução mais eficiente e adequado para modelos de programação linear, que é o modelo mais utilizado para representar o planejamento de cadeias de suprimentos descentralizadas.

Por fim, um procedimento estruturado para a aplicação de planejamento colaborativo e descentralizado em cadeias de suprimentos de peças de reposição integradas a sistemas inteligentes de manutenção é proposto. O procedimento é implementado em um caso teste através de simulação para a verificação de sua factibilidade bem como sua comparação com uma abordagem clássica de gestão.

CONCLUSÕES

Através desse trabalho é possível formar algumas conclusões sobre o tema, originadas das aplicações feitas em cada capítulo.

Primeiramente, através de uma análise na literatura, é possível concluir que o desenvolvimento de modelos de planejamento descentralizado está relativamente avançado, sendo possível encontrar várias propostas para o mesmo na literatura. Porém, boa parte dos modelos não são devidamente validados em casos testes com dados reais, ou até aplicações reais. Além disso, quando se trata de métodos de resolução dos modelos de programação linear, poucos autores justificam suas escolhas.

Através de uma revisão sobre métodos de resolução de programação linear foi possível concluir que há poucos critérios técnicos e objetivos para embasar a escolha dos mesmos. Uma tabela com critérios qualitativos e sugestões foi construída para auxiliar na escolha do método.

Por último, o procedimento estruturado proposto para aplicação de planejamento colaborativo descentralizado em cadeias de suprimentos de peças de reposição integradas a sistemas inteligentes de manutenção se mostrou efetivo e eficiente, gerando um melhor resultado em termos de custos comparado ao modelo Naïve mesmo sob níveis mais baixos de confiança da previsão fornecida pelo sistema inteligente de manutenção.

LISTA DE FIGURAS

LISTA DE QUADROS

LISTA DE ABREVIATURAS E SIGLAS

SC – Supply Chain
SCM – Supply Chain Management
SPSC – Spare Parts Supply Chain
LP – Linear Programming
CP – Collaborative Planning
GA – Genetic Algorithm
ACO – Ant Colony Optimization
FRISCO – Framework for Intelligent Supply Chain Operations
3PL – Third Part Logistics
PA – Production Agent
DA – Distribution Agent
Max – Maximize
S.T. – Subject to
IMS – Intelligent Maintenance Systems
DC – Distribution Center

SUMÁRIO

INTRODUCTION

Machines and equipment employed in the industry suffer degradations of different types throughout their use, limiting their useful life. Machines failures caused by physical-chemical degradations in their components - such as wear, oxidation, dirt, corrosion, cracks, among others - are quite common in industrial processes (COHEN et al., 2006).

These occurrences can become a major problem if not treated with agility, generating downtimes and bottlenecks in the production, which is extremely damaging to an organization's productivity and competitiveness levels in a broad market where survival is a daily challenge.

Therefore, manufacturing companies basically use four groups of maintenance strategies (LEE et al., 2004) to avoid downtimes caused by part failures: (i) corrective maintenance, which consists in the equipment’s repair after the occurrence of failures; (ii) preventive maintenance, more contemporary, corresponds to actions planned, prepared or scheduled before the probable occurrence of the failure; (iii) predictive maintenance, which occurs when a continuous monitoring and controlling of the performance parameters is applied (QIU et al., 2006); (iv) proactive maintenance (or intelligent maintenance), which monitors the equipment or process, in addition to diagnosing and quantifying the loss of system performance over time.

With the current state of microelectronics and software development, a new maintenance approach can be introduced: condition-based maintenance. In the condition-based maintenance, physical information on each part of the machines will be given in real time, while algorithms developed by Intelligent Maintenance Systems (IMS) will provide the parts’ breakdown forecasts and increasing costs. Information will be given by sensors and embedded systems, while health-estimation algorithms will predict the failures. Breakdown forecasting is not only important to improve maintenance but also to inform the whole supply chain to support the demand planning on a tactical and operational level (FRAZZON et al., 2014).

Supply chains have a higher degree of complexity in the case of spare parts; classic forecasting models are not the most suitable for their planning due to the large component variability and the erratic pattern of demand (HELLINGRATH and CORDES, 2013). For improved efficiency and effectiveness, integrated spare parts supply chain (SPSC) planning is essential, allowing better communication between agents and concurrently improving chain operations (FREDENDALL and HILL, 2001). The use of information on the machines' conditions and spare parts obtained through the IMS are necessary inputs for the programming and planning of SPSC. This strategy increases the performance of maintenance services and facilitates the evaluation of the condition of these spare parts (FRAZZON et al. 2014), resulting in a better service level and in the reduction of operating costs.

In general, spare parts need to be available at appropriate locations within the supply chain to ensure the desired level of service. However, several aspects make this task challenging, for example, the high number of parts to be managed, irregular demands, the high responsibility required due to the cost of customer inactivity, the risk of obsolete stocks, among others.

The demand characteristics of spare parts and the required service levels make daily production and logistics management processes challenging. Because of this complexity, SPSC management processes cover different areas of knowledge, which in turn use a variety of resources, methods, techniques for solving various problems (ISRAEL, 2014).

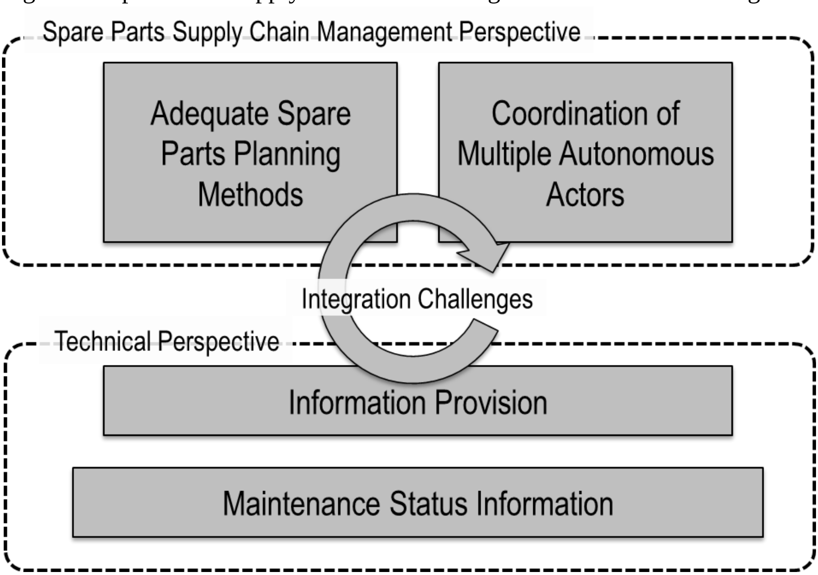
According to Espíndola et al. (2012), the availability of spare parts and maintenance services is crucial to the operation of manufacturing systems. The lack of repair components has negative cost effects, such as high opportunity costs and high costs of emergency orders in distant regions. Given the potential difficulty of meeting deadlines each time a break occurs, the company may not be able to reach the level of service desired, harming the relationship with customers.

Based on the literature, Israel (2014) also emphasizes that it is possible to identify three salient characteristics of SPSCs. The first refers to the pattern of demand, which tends to be intermittent and/or erratic, hindering forecasting processes by classical statistical methods and inventory control (BOYLAN and SYNTETOS, 2010). The second characteristic refers to the high levels of services required. According to Huiskonen (2001), maintenance components need to be available as soon as a failure occurs, otherwise, the production systems may become unavailable, causing high costs for their companies". The author also mentions that a distribution network with hierarchically organized multi-tier stocks, in different locations, becomes necessary to meet demands and quality. The third and final characteristic, described by Israel (2014), derives from the previous two - as there is a great variation in demand and a capillary network of stocks, distribution costs are high. In periods of low demand, inventories continue to be necessary for high demand periods, making distribution processes more expensive.

Considering these concepts, it takes detailed planning of the spare parts supply chain to meet service levels and minimize costs. Such planning can be carried out at strategic, tactical and operational levels, all of which are equally important. Regarding the planning of SPSCs, the two segments that will be used as references for the practical application of this work are Intelligent Maintenance Systems and Integrated Planning.

Espíndola et al. (2012) realize the need for integration between Intelligent Maintenance Systems and Spare Parts Supply Chains and describe the challenges of this integration in three levels, as illustrated in Figure 1 and Figure 2. The first challenge is at a technical level, which concerns the acquisition of information on components and fault predictions. At the second level, comes the managerial challenge of choosing and executing planning methods and coordinating the different actors within the chain. Finally, there is the difficulty of integrating the two systems and the simultaneous and somewhat conflicting search for effectiveness (to perform the right maintenance on time) and efficiency (low maintenance costs).

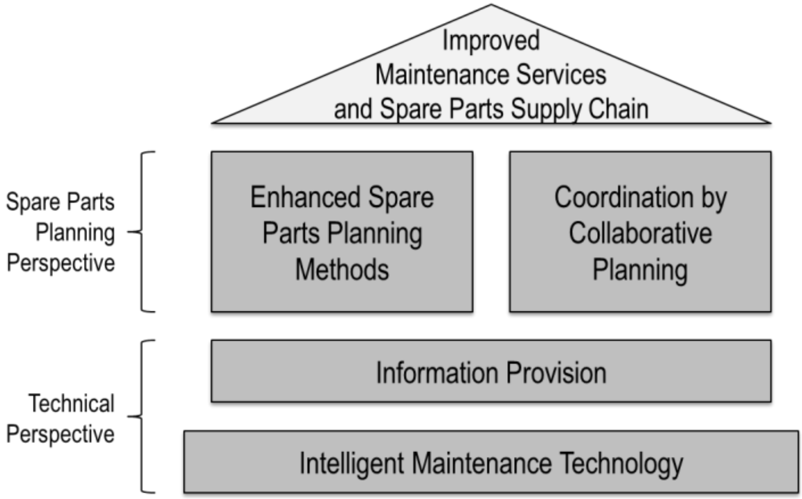
Figure 1 - Spare Parts Supply Chains and Intelligent Maintenance challenges



Source: Espíndola (2012)

In view of this, Espíndola et al. (2012) have developed a research project that provides the basis for building an effective integration between IMS and SPSCs.

Figure 2 - Global view and high-level components



Source: Espíndola (2012)

Focusing on the managerial perspective, Israel (2014) proposes a mathematical model for optimization at the operational level of the transportation and storage strategy of a spare parts supply chain. This model proved to be effective through simulations but still has improvement points for further studies.

In this work, a systematic overview on collaboration in supply chain planning is presented to verify the main advances and research opportunities. One of the conclusions of the systematic overview is the lack of applicability hierarchical models (models that assume the planning to be centralized in one chain participant while the others always agree with the plan) have. The model presented by Israel (2014) establishes a hierarchical system, optimizing the total costs of the chain, disregarding the individual objectives of the participating agents and the confidentiality of their information. Dudek and Stadtler (2005) and Jung (2008) consider that a hierarchical planning model can be inconvenient for the privacy of the organization, and both studies propose decentralized planning approaches, where the optimization is usually divided between actors that exchange minimum information among each other.

Another issue depicted in the systematic overview is the models' lack of application in real cases or test cases with real data. Therefore, the relevance of the present work is justified by the necessity of support for the implementation of collaborative decentralized planning in spare parts supply chains, which lacks application examples according to the literature. The present work aims to provide a procedure to guide such applications.

1.1. OBJECTIVES

1.1.1. General objective

The general objective of this work is to propose a structured procedure to support an efficient application of collaborative decentralized supply chain planning for spare parts supply chains integrated to intelligent maintenance systems.

1.1.2. Specific objectives

The specific objectives of this work are:

- Identify trends and research opportunities in the area;
- Gather characteristics that help to choose a resolution method for the most used modeling method for optimizing decentralized supply chains;
- Elaborate a simulation model to analyze the results provided by the optimization model and its stochastic performance;
- Implement the constructed mathematical and simulation models in a test case.

1.2. LIMITATIONS

Some limitations shall be considered in the application of the present work.

The bibliographical and bibliometric analyses consider only documents written in the English language from three databases: Web of Science, Scopus and Science Direct.

No statistical analysis is performed for the selection of the most used solving methods. The characterization of which methods are most used is based on other studies.

An already validated mathematical model was selected to be employed in this work. The development of a new mathematical model is not in the scope of the present research.

1.3. DOCUMENT STRUCTURE

The present work is a compendium composed of three scientific papers elaborated during 2016, submitted/approved for publication in conferences and journals. More information on the papers is shown in the table below (Table 1).

Table 1 - Papers

Paper	Authors	Journal / Conference	Research question
Collaboration in Supply Chain Planning: A Literature Review	Pires, Matheus Cardoso; Frazzon, Enzo Morosini; Holz, Túlio Henrique	Submitted to Journal of Manufacturing Technology Management	What are the main gaps and research directions on collaboration in supply chains?
On the research of linear programming solving methods for non-hierarchical spare parts supply chain planning	Pires, Matheus Cardoso; Frazzon, Enzo Morosini	Published on proceedings from 4th IFAC Symposium on Telematics Application	Which is the best solving method to apply in non-hierarchical spare parts supply chain planning?
Collaborative operational planning for decentralized spare parts supply chains	Pires, Matheus Cardoso; Frazzon, Enzo Morosini; Silva, Lucas de Souza; Holz, Túlio Henrique; Saalman, Philipp; Hellingrath, Bernd	Submitted to Computers and Industrial Engineering Journal	What are the main steps for an efficient implementation of collaborative decentralized supply chain planning in spare parts supply chains?

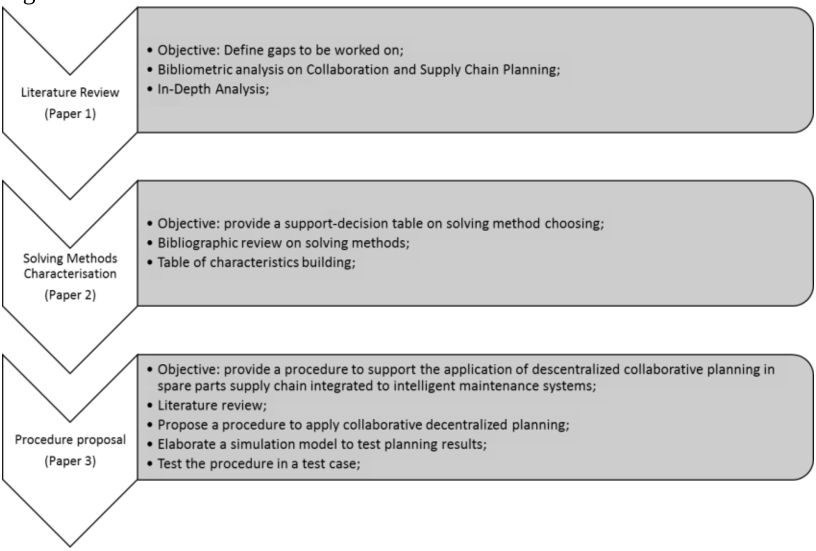
Source: Author

Chapter 2 presents the first paper from the table above and the literature review on Collaborative Planning and Supply Chains, identifying gaps and research directions, describing the starting points from which the current work elaborates on. Chapter 3 depicts the second paper from Table 1, which explores the best approach for solving the most used models to generate plans for decentralized collaborative supply chains. Finally, chapter 4 presents the third paper, and a method is applied to find a matching mathematical model to generate a plan for decentralized supply chains. Subsequently, the model is tested and compared to a classical approach through simulation.

1.4. RESEARCH METHODS AND TECHNIQUES

In order to fulfill the objectives of this work, as previously described, a research plan was designed and divided into three main steps, as shown in Figure 3. Each step was reported in a different paper, presenting its own objective and methodology (Table 1).

Figure 3 - Research content



Source: Author

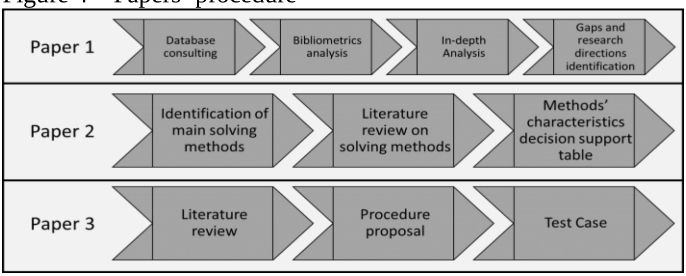
In the first step, a bibliometric analysis and an in-depth analysis were carried out on the topics of Collaboration and Supply Chain Planning. The research was performed in reference databases that are composed of a large number of journals on the subject. A data analysis software was employed to verify tendencies and perform an optimized reading of the extracted data so that better conclusions could be reached. The objective of the first step (reported in Paper 1, presented in Chapter 2) was to identify trends and gaps to be worked on in posterior works.

In the second step (Paper 2, presented in Chapter 3) a new literature review was carried out with the objective of identifying the most used mathematical modeling methods on the planning of decentralized supply chains. With this result, a new bibliographic research was performed to build a decision support framework for choosing the most appropriate solving method for the most used modeling method. The necessity of this step was defined based on the conclusions reached from step 1.

In the third step (Paper 3, presented in Chapter 4), in order to propose a structured procedure for applying decentralized collaborative planning in spare parts supply chains integrated to intelligent maintenance systems, a literature review was performed on this specific issue. A test case was employed to validate the procedure. For this, a real spare parts supply chain was taken as an example, a collaborative decentralized planning model was proposed, implemented, and tested through simulation. The necessity of this step was also defined based on the conclusions from step one.

Looking at the bigger picture, step one aimed to provide a better understanding of the research area, its main concepts, problems to be solved, as well as the main approaches for solving them. Step two explored the research gaps indicated by step one and aimed to support decisions in the execution of step three. Step three emerged from another gap pointed out by step one and aimed to support the application and validation of decentralized collaborative planning in today's supply chains. This procedure is shown in Figure 4.

Figure 4 – Papers' procedure



Source: Author

Silva and Menezes (2000) proposed a research classification divided into four categories, regarding the research's nature, approach, proposed objectives and the technical procedures adopted by the researcher. In relation to its nature, the present work is an applied research that intends to generate knowledge to guide the solution of specific problems. Regarding its approach, this is a quantitative work, since the result of the proposed procedure is evaluated according to its cost reduction performance through a simulation. Regarding its objectives, this research is exploratory, for it offers a closer look into the problem, providing a better general understanding. Regarding the technical procedure, this work employs both a bibliographic research and an experimental research. The bibliographic procedure is used to understand concepts, advances, and research opportunities, while the experimentation (through a simulation model) is used to verify the applicability of the proposed procedure.

2. COLLABORATION IN SUPPLY CHAIN PLANNING: A LITERATURE REVIEW

Considering the objectives presented in the last chapter, this work requires an overview of the current topics on collaboration in the planning of supply chains.

The present section thus aims to build an overview of the scientific literature on collaboration in supply chain planning to establish the main concepts and tendencies of the subject and to identify gaps and opportunities in the literature, as well as to assess its evolution.

A bibliometric analysis and an in-depth analysis were performed to reach such objectives. The results from these analyses were used to support the research objective of the current work and also to guide the papers presented in chapters three and four to solve the main gaps found in the research area.

2.1. INTRODUCTION

Several definitions for supply chain can be found in the literature. Indeed, they are all similar to the definition provided by Kozlenkova (2015), which characterizes it as a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities involve the transformation of natural resources and components into a finished product, which is delivered to the end customer. In this context, we can also define the concept of supply chain management, which consists in the designing, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally.

Globalization has made chains strive to achieve better results in terms of cost and efficiency as the customers are increasingly rigorous and the environment is highly dynamic. Modern business management faces the challenge of individual businesses no longer competing as solely autonomous entities but rather as supply chains (LAMBERT and COOPER, 2000). Therefore, supply chain management (SCM) is considered to involve integration, coordination, and collaboration across organizations and throughout the supply chain (STANK et al., 2001). Collaboration in the supply chain comes in a wide range of forms but, in general, has a common goal: to create a transparent, visible demand pattern that paces the entire supply chain (HOLWEG et al., 2005). Some of these efforts are related to the adoption of collaborative planning concepts in the supply chain management. According to the current literature, collaborative planning can be described as a conceptual framework for resolving complex, multi-stakeholder planning scenarios. For Dudek and Stadtler (2005), collaborative planning is the coordination process of autonomous yet interconnected master planning activities. This approach is often applied for encouraging public participation and resolving and mediating stakeholder disagreements. While the literature mentions some challenges in evaluating collaborative planning, Day and Gunton (2003) suggest four common criteria to measure its effective use, including: (1) the ability to successfully reach agreements, (2) efficiency in the collaborative process, (3) stakeholder satisfaction in the planned outcome, and (4) achievement of social capital among stakeholders. Moreover, different approaches and methodologies have been employed by researchers to evaluate the effectiveness of the application (or the level of application) of such concepts in the supply chain management.

According to Stadtler (2009, page 5), "one important way to achieve coordination in an inter-organizational Supply Chain (SC) is the alignment of future activities of SC members, hence the coordination of plans". Thus, a collaborative SC strategy recognizes that integrated business processes value customers. Therefore, several supply chain elements, namely strategy/policies/processes, structure, relationships, and coordination/control have been utilized to discuss spare parts management in the context of supply chain development. Huiskonen (2001) argues that the only way to bring the conflicting views of suppliers and customers into alignment is through the collaborative design of the logistical network structure as a whole. The author also emphasizes the importance of information exchange at an early stage, particularly in multi-echelon inventory systems where "control and coordination in inter-organizational settings need not always be based on hard formal systems but are often achieved by 'soft' means through trust and commitment between the parties".

Kopczak and Johnson (2003) explored important aspects of integrated management of logistics processes and their effects on business competitiveness and the creation of value. According to the authors, ongoing changes were forcing companies to re-examine their business vision and redefine on which processes they will focus their resources and skills. Added to this, the resulting interorganizational network consists of several autonomous companies, which cannot necessarily be forced to follow decisions, strategies or plans of a superordinate unit. Thus, “the effective and efficient management and hence coordination of such SCs cannot be achieved in the same way as in hierarchical organizations which can be controlled by one dominant actor” (HELLINGRATH and KÜPPERS, 2011a).

The main problem is to equate material and information flows that run throughout the supply chain. In other words, the better known and monitored these flows are, the lower the necessity will be for safety stocks to attend demand and production requirements (FERROZZI et al., 1993; CHRISTOPHER, 1997). This means that the less information the company has, or the poorer the information flows are, the more necessary the safety elements will be to meet the fluctuations in demand, which brings direct impact on the organization’s profit margins. This lack of decisional and organizational integration leads to inefficiencies related to poor coordination of production and distribution decisions and results in missed opportunities, delays, inefficient inventory decisions, poor capacity allocation, and misuse of resources, all leading to increased cost (LEE et al., 2004).

Frayret (2009) mentions that the problem “consists in synchronizing the supply chain partners’ usage of their resources in order to avoid shortage and make sure materials, components and final products flow continuously whenever needed by downstream partners, at minimal cost”. Thus, decisions such as what and when to produce and deliver become crucial points in business strategies. The author also highlights that an important feature of this coordination issue is its distribution nature. In other words, the companies have different processes, decisions, and strategies in the supply chain, and consequently, in general, they can make any decision and follow any decision process they want. Thus, the most challenging aspect of this problem is to provide a solution that meets this distributed nature.

Collaborative planning (CP) concepts address these necessities by avoiding centralized planning or decision-making components and by relying on a coordination based on mutual agreement, without the exposure of private information and loss of local decision autonomy of the companies (HELLINGRATH and KÜPPERS, 2011a).

A traditional planning model for hierarchical supply chains can, therefore, either describe only part of a distributed supply chain, a single given actor or encompass all links of all actors in a supply chain, which is unlikely in today’s complex production networks. Moreover, the supply chain actors are often not willing to share strategic or sensible information (BREITER et al. 2009), which can affect research streams in this area.

In this scenario, the objective of this chapter is to summarize the scientific literature on collaborative supply chain planning, characterizing current research gaps and opportunities by tracking the most important articles and understanding the similarity between studies and their current gaps. A total of 55 papers were selected from three databases to build a collection for the bibliometric analysis, and seven of them were used for an in-depth analysis.

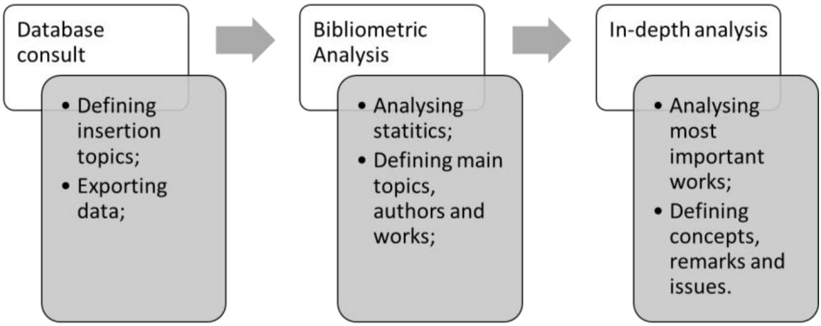
This chapter is composed of four main sections. In section 2.2, Methodological Procedure, the methodology to be applied is explained, including the steps of each process, utilized databases, search topics, software and tools. Subsection 2.2.2, Bibliometric Analysis, is composed of the statistics prospected from the collection obtained in section 2.2.1, as well as a discussion on the results. Section 2.4, In-depth Analysis, presents a deeper view of the most important works in the collection and some interesting observations. Section 2.5, Gaps and Findings, is used to identify the main trends and future research opportunities.

2.2. METHODOLOGICAL PROCEDURE

The initial steps of the methodological procedures were based on searches from Web of Science, Scopus and Science Direct, databases that have a large number of works on the topics of interest. Suitable data was exported to an analysis software, and a bibliometric analysis was performed using the software EndNote X8, Hammer Nails Project, and VOSViewer. Some analyses in certain software are only possible to be executed with output data from a specific database; this consideration will be mentioned when each analysis is presented.

From the search results, it was possible to identify the main papers in the field, as well as their contents. Figure 5 presents the steps of the methodological procedures.

Figure 5 - Methodological procedures' main steps



Source: Author

2.2.1. Dataset collection

The dataset was retrieved from Web of Science using the search parameters presented in Table 2.

Table 2 - Search parameters

Databases	Web of Science, Scopus and Science Direct
Topics	Collaborat* AND "Supply Chain Plan*"
Research Areas	All
Document types	Research paper, Review paper

Source: Author

Other databases were not taken into account for this analysis due to software limitations. Nevertheless, the three databases (which presented a good number of intersections of journals and proceedings) are expected to be sufficiently representative of the scientific literature in supply chain.

The searched topics were inserted exactly as shown in Table 2. The word Collaborat* can return the topics that include Collaboration and its variants, as Collaborative, as well as "Supply Chain Plan*" returns topics on Supply Chain Planning and the variants of the word Planning.

2.2.2. Bibliometric analysis procedures

The first step of the analysis is done using EndNote, and it consists in the gathering of statistic data from the collection, for example, volume of publication by year and most occurred keywords. EndNote is used in this step due to its characteristic of working with different types of data. However, EndNote does not allow the user to import information on references and citations.

The second step of the analysis is done by identifying the important authors, journals, articles, and keywords in the dataset based on the number of occurrences, co-occurrences and citation counts. Web of Science retrieves a citation network dataset that is used to identify the most important papers with the Hammer Nails Project tool. The main authors are identified by the number of works in the dataset, and the citation by the articles in the dataset. The most important papers are identified using three measures:

1) The in-degree in the citation network, which is the degree of node centrality, considering the weights of the nodes each node is connected to (KNUTAS et al., 2015);
2) The citation count provided by Web of Science;
3) The PageRank score (PAGE et al., 1999) in the citation network.

The analysis also found often-cited references that were not included in the original dataset. Several authors analyzed an article's relevance by examining its backlink count, the number of articles that cite it, generally hypothesizing that more backlinks means higher importance (PAGE et al. 1999).

By utilizing the text mining software VOSViewer, the co-citation analysis was performed by creating a distance map (VAN ECK and WALTMAN, 2010) with the references cited by the papers on the dataset collection. The main clusters of the dataset research are defined by the distance map, which shows the references that are commonly cited together.

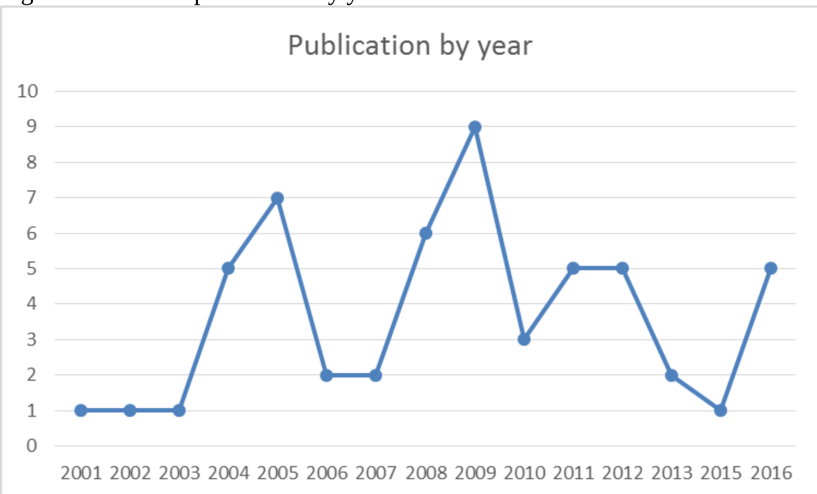
A pair of articles is considered to be "co-cited" when they both occur in the same reference list of a third article. Citation overlap between documents or frequent co-citation of two documents was proven to be a strong indicator of document similarity (BOGERS et al., 2008).

2.3. METRICS RESULTS

In the present section, the numerical results obtained by the previously explained methodology will be shown. The search was done on Web of Science, Scopus and Science Direct databases with the keywords Collaborat* and “Supply Chain Plan*”, obtaining 15 results on Science Direct, 45 on Web of Science and 95 on Scopus. After removing the duplicates (or triplicates) and the ones out of context (as a keyword may be mentioned in the abstract, but the work might not deal with the topic), 55 articles remained. Papers considered out of context were those that appeared in the collection due to the use of some keywords in the abstract section but do not explore the actual topic, for example, a hardware architecture design to support a collaborative distributed supply chain. This selection was done by reading titles and abstracts.

Figure 6 shows the number of scientific papers published per year on the above-mentioned databases. The graph was built with data exported from EndNote, representing data from the three databases.

Figure 6 - Volume publication by year

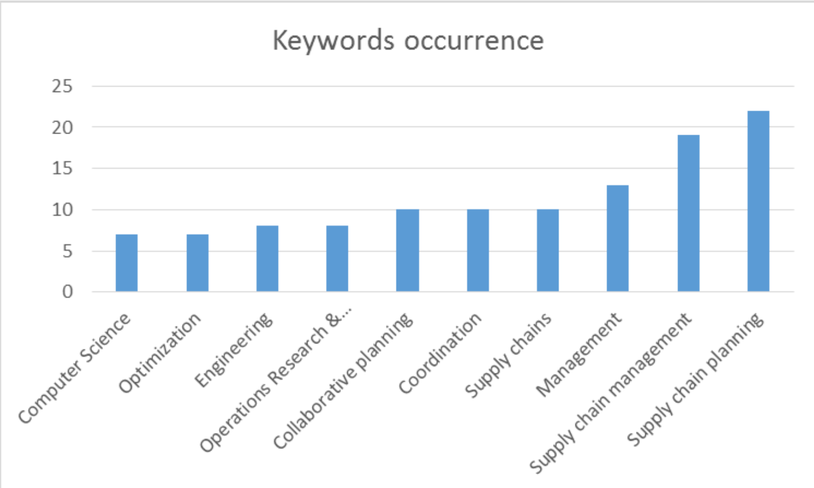


Source: Author

The topic of collaborative supply chain planning had a considerable growth since its first appearance, reaching its peak around 2009. As can be seen, there is no clear growth tendency over the years, but an average occurrence is maintained every year. A possible explanation for this behavior is that the search deals with a very specific topic and not a whole area. The publication volume can be affected by the existence of big conferences exploring the issue, as is the case of 2009, when most papers were published on conferences or journals exploring the subject in certain editions.

In Figure 7 it is possible to see the most mentioned keywords in the title and abstract fields of the works indexed on the databases.

Figure 7 - Keywords occurrence

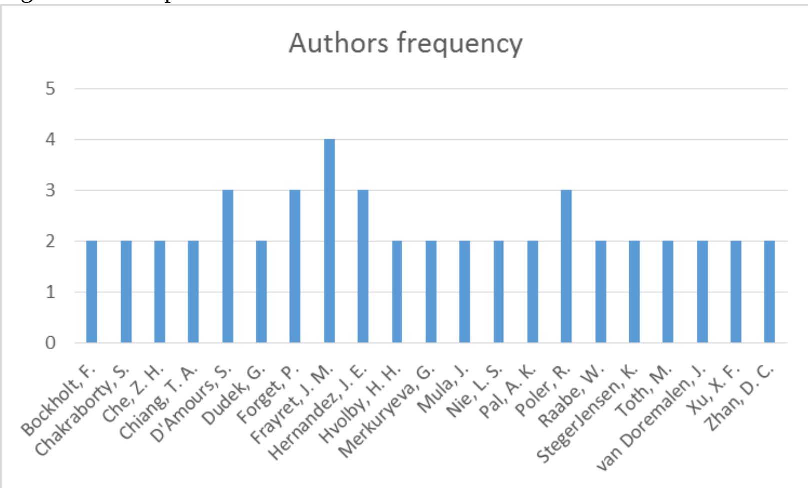


Source: Author

As expected, Supply Chain Management and Supply Chain Planning are the most common keywords among the scientific papers. In addition, it is interesting to notice the presence of the word Coordination, which in collaborative planning has as one of its goals to minimize waste caused by the Bullwhip Effect (or Forrester Effect). It is interesting to notice the presence of the words Operations Research, Optimization and Computer Science, suggesting that most papers on the subject deal with Linear or Non-Linear Program Modeling and their solving methods.

Figure 8 shows a representation of the most frequent authors of the collection comprising the three databases. The most productive authors are from the quantitative stream of supply chain studies and are strongly connected, as will be shown posteriorly.

Figure 8 - Most productive authors

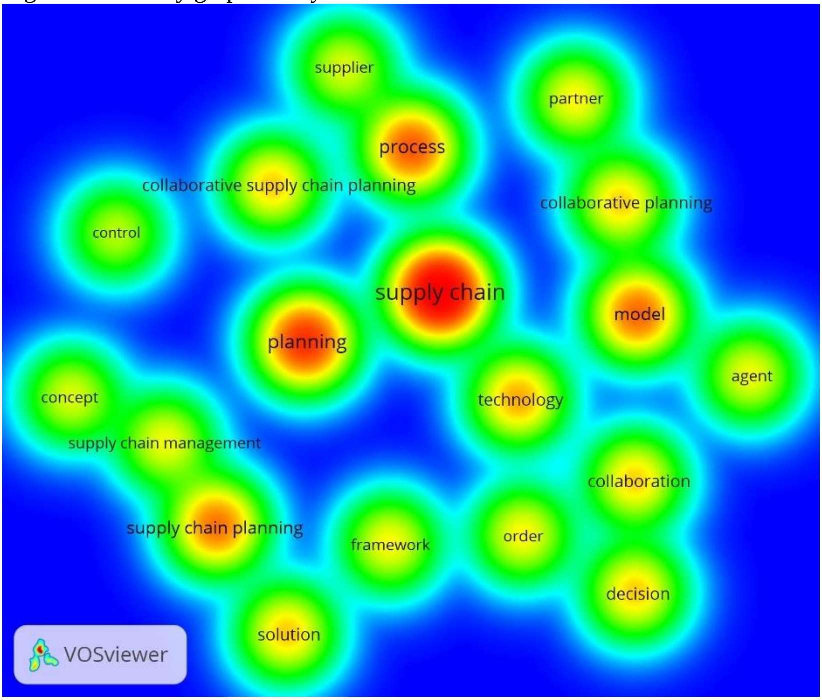


Source: Author

Figure 9 shows a density graph of the network visualization on the main topics created using VOS Viewer software. For this analysis, the software accepts the RIS file provided by EndNote, comprising the three databases. The software builds a network according to the relationship between words and gives each word a density according to the number of co-occurrences and the weight of the words that are connected. For this visualization, the title and abstract fields were analyzed. Binary counting was performed, meaning that each word can be counted at maximum once in each title and abstract, not considering how many times it appears on both sections. Only words with a minimum of 8 occurrences were considered to build the network. With the exception of the word "paper", which was removed from the list, 100% of the most relevant terms were considered, despite the software's standard being 60%.

The density graph shows that the words "supply chain" and "planning" are the most recurrent, as well as "model" and "process", suggesting that the main objective in the area is to design ways for this collaboration to become real and effective.

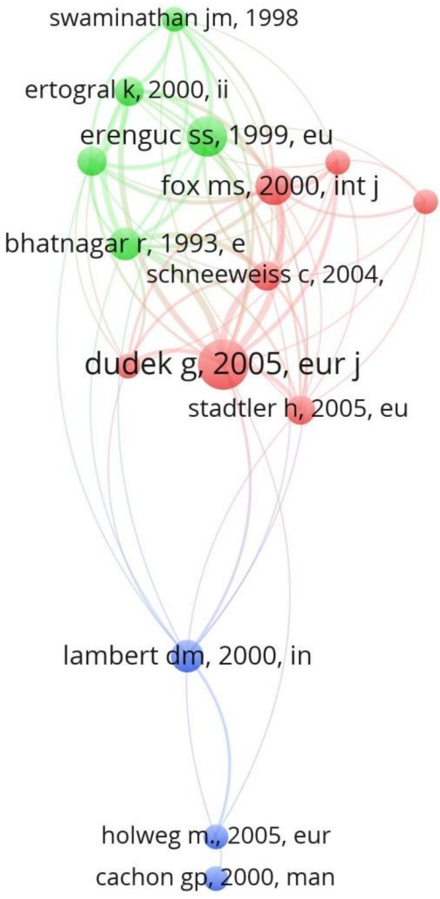
Figure 9 - Density graph of keyword network visualization



Source: Author

Figure 10 shows the network built to represent the most relevant works and their connections. For this, only files from Web of Science were considered. The relationship between the nodes is established by co-citations. Only papers with a minimum of four citations were considered.

Figure 10 - Co-citation network

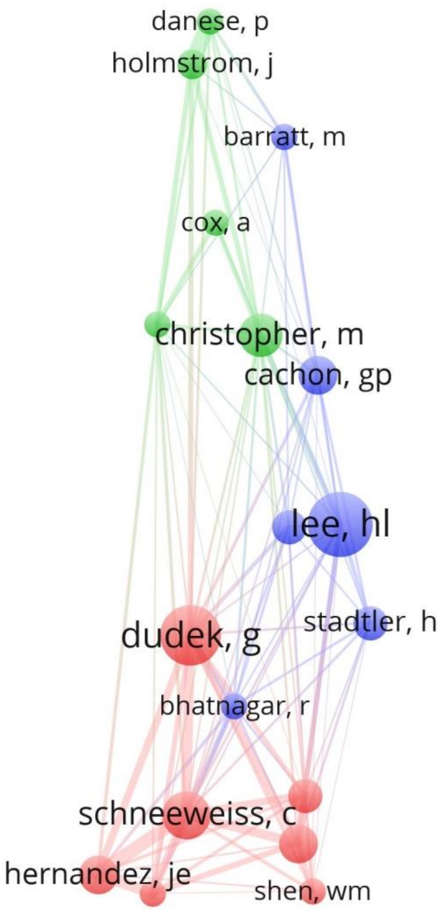


Source: Author

Figure 11 shows a network of the main authors. The relationship of the nodes, the thickness of the arches and the division by clusters are defined by the relationship between authors in terms of co-citation. In this network, only data from Web of Science and authors with a minimum of 6 citations were considered.

Red clusters comprise the most productive authors according to the previously mentioned statistics. These authors usually work on the Operations Research area.

Figure 11 - Authors' co-citation network



Source: Author

2.4. IN-DEPTH ANALYSIS

In the present section, a ranking of the most important works of the area will be presented, as well as a short description of each one.

Table 3 - Papers submitted to an in-depth analysis

Authors	Title	Year	In-degree
Dudek, G. And Stadtler, H.	Negotiation-based collaborative planning between supply chains partners	2005	11
Jung, H.; Chen, F. and Jeong, B.	Decentralized supply chain planning framework for third party logistics partnership	2008	4
Forget, P.; D'Amours, S. and Frayet, J.	Multi-behavior agent model for planning in supply chains: An application to the lumber industry	2008	1
De Kok et al.	Philips electronics synchronizes its supply chain to end the bullwhip effect	2005	1
Forget et al.	Study of the performance of multi-behavior agents for supply chain planning	2009	1
Makatsoris, H. And Chang, Y.	Design of a demand-driven collaborative supply-chain planning and fulfilment system for distributed enterprises	2004	1
Alftan, A.; Kaipia, R. and Loikkanen	Centralized grocery supply chain planning: improved exception management	2015	1

Source: Author

The seven most important scientific papers are listed in Table 3. The importance was measured according to their in-degree level, as presented in the methodology section. The papers with an in-degree index greater than zero were considered the most important because of their relationship with other scientific works in the area.

Alftan et al. (2015) state that the groceries supply chain still faces some challenges on replenishment planning despite the technological advances it has undergone. One of these challenges, the demand exceptions, is highlighted by the author. The author affirms that Vendor Managed Inventory and Collaborative Planning, Forecasting and

Replenishment do not always overcome the challenge since downstream information is not enough to deal with exceptional demands. Alftan et al. (2015) then propose a Collaborative Buyer-Managed Forecasting that turns the centralized forecasting by the closest agent to the customer in a plan for the whole supply chain by creating a so-called one-order forecast.

Makatsoris and Chang (2004) reinforce the necessities of collaboration and dynamic planning systems in order to be efficient in a competitive world. For the authors, many cooperation models have been proposed, but they lack a logical system to make them applicable. The authors then propose a system capable of performing a demand-driven collaborative supply chain planning and fulfillment for distributed enterprises.

Forget et al. (2008) and Forget et al. (2009) state that competitiveness is directly connected to supply chain performance and coordination is essential between organizations to reach performance. However, to reach coordination and performance, an advanced planning system is needed for the company to be able to adapt to different scenarios. The authors then propose a multi-behavior planning agent model supported by a distributed planning system. In preliminary tests in a lumber supply chain, the authors show a potential gain in supply chain performance.

De Kok et al. (2005) present the Bullwhip Effect problem in the Philipps Semiconductors' Supply Chain and how the performance increased leading to millions of dollars saved each year with the application of stochastic multi-echelon inventory in an advanced planning and scheduling system that supports the collaborative planning of operations in the supply chain.

Jung et al. (2008) reinforce the necessity of collaboration and synchronization in order to reach competitive performance levels in today's dynamic scenario. Therefore, in supply chains where the logistics operations are done by outsourced companies, the amount of information shared is usually reduced to preserve the privacy of each business, reducing the application of centralized planning. The authors then propose a decentralized planning optimization model for third part logistics partnership with minimum information sharing. Through computational tests, the model presented good results in comparison to centralized planning results.

Some years earlier, Dudek and Stadtler (2005) had pointed out the same necessity as the previous authors, defining that synchronization and coordination are indeed necessary for supply chain performance, but the application of hierarchical (centralized) planning is often rejected by the market due to the loss of privacy resulted from information sharing. The authors propose a set of mathematical models to optimize and generate plans for the supply chain actors. The models are based on negotiation and consist of steps executed iteratively in order to represent a negotiation until they converge to a plan of material flows. According to tests, the plan resulted from these models provides solutions similar to those provided by centralized planning but with minimal information sharing.

In a less deep analysis of other titles provided by the search, it is possible to notice that methods of collaborative planning are still an issue and are still being developed nowadays, as in Zhou et al. (2015), hsu et al. (2016), Schuh and Hering (2013), and Li et al. (2011). Terwiesch et al. (2005), for example, use game theory approaches. The authors, in an empirical study in a semiconductor supply chain, found that forecast sharing has the potential to improve the SC, although this does not happen. This means that the supplier penalizes the client with delays, which forces the client to inflate its orders, in a tit for tat logic where the Nash Equilibrium is never reached. Studies such as Soosay et al. (2008) assume a more qualitative approach, while studies such as Selim et al. (2008) and Muckstadt et al. (2001) use mathematical modeling (linear programming, fuzzy-goal, etc.) approaches to evaluate the benefits of collaboration in supply chains.

Other efforts can be frequently seen, as in Gaudreault et al. (2016), in which technologies are still being developed for the successful implementation of a dynamic supply chain planning. There is still room for improvement in the anticipation of performance, as in Chen (2015).

2.5. FUTURE RESEARCH OPPORTUNITIES

The model proposed by Alftan et al. (2015), however, is neither generic nor has quantitative data on its performance. Regarding Collaborative Buyer-Managed Forecasting, the model can be adapted and/or has its performance measured over different scenarios. Different approaches can also be developed to supplement the application of Collaborative Planning, Forecasting and Replenishment, and Vendor Managed Inventory, since, according to the authors, their potential is generally limited when dealing with exceptional demands.

Makatsoris and Chang (2004) affirm that today’s market provides many state-of-the-art technologies for supply chain management.

However, most of them do not consider the specific characteristics and practical considerations of the environment of these distributed systems, creating the opportunity to design more customized systems for each supply chain organization.

Forget et al. (2008) and Forget et al. (2009) define three interesting research directions regarding multi-behavior agents for supply chain planning systems. The first is to test the methodology over rolling planning horizons to clarify the possibility of gains through its application. Second, different approaches to insert a learning ability can be implemented in the agents to enhance their potential over time. Finally, the behaviors of anticipation and negotiation can be implemented in the agents to better explore the potentials of the methodology.

Jung et al. (2008) point two research opportunities beyond their work. The first is to validate the model using data from real companies with third-party logistics partnership. The second is to extend the planning model in order to consider multiple service providers, which would be the case for a big number of supply chains in today’s market.

Dudek and Stadtler (2005) clarify that their model is not able to analyze the situation, leaving a gap for an extension in adaptive planning models or even self-learning systems. In addition, the model can be extended to a rolling planning horizon mode, where the planning is re-executed periodically. The authors also indicate that extensions to supply chains with several buyers and suppliers can be interesting.

In addition to the gaps identified by these authors, it is clear that most of the development in the area, as planning models, frameworks and technologies, lack practical application or at least test cases with real data from real supply chains. These applications and tests can clarify the applicability of such advances in different supply chains. For example, some planning models that aim to dropdown the stock levels to zero may not be suitable in supply chains with high demand variance and, consequently, high forecasting complexity.

Also, when dealing with operations research, there are few studies discussing the choice of solving methods, and most of the works utilizes randomly chosen solving methods. The choice of the solving method can be crucial for the planning model’s performance, as some solving methods do not guarantee optimal solutions and others cannot solve the problem in a feasible time, depending on the problem’s size.

2.6. CONCLUSIONS

This chapter presented a systematic bibliometric analysis and an in-depth analysis on the topics “Supply Chain Planning” and “Supply Chain Collaboration”. For this, EndNote, VOS Viewer and Nail Project software were employed. The data search returned 55 papers from three databases over the last 16 years since these topics first appeared in the area. The seven most important papers were selected for an in-depth analysis to indicate the principal research directions and its main gaps.

Six bibliometric analyses were performed aiming to identify tendencies in the research area. The volume of publications per year show that the topic collaboration in supply chains started to appear in scientific papers in 2001 (as there was no time limitation in the performed search), increasing in number in 2005 and reaching its peak in 2009. Nevertheless, it is still a researched topic nowadays. Analyzing the most occurred keywords, it is possible to conclude that coordination is the main goal of collaboration in supply chain planning; the majority of the studies are performed in the operations research area and its computational implications. The graph of the most productive authors shows important researchers and institutions behind the development of the topic, and that a large part of the advances is concentrated in the quantitative area. The network of keywords leads to the conclusion that the advances focus on developing models and processes for planning and information sharing. The network of main works and authors shows a centrality of the author Dudek G. and his works on decentralized planning, as well as his strong connection with other quantitative authors that develop collaborative planning methods.

The in-depth analysis reinforces the conclusions reached from the network of keywords, clarifying the stream of studies on the development of models and methods to plan and coordinate the supply chain in order to reduce, mainly, the bullwhip effect in such a dynamic scenario. This further suggests that the current models for supply chain planning and coordination may not have reached their state-of-the-art yet.

Therefore, most of the authors indicate that the studies lack practical application or test cases applied in real scenarios; these applications are needed to validate the employment of the developed technologies in the real world. In addition, when it comes to operations research, most of the chosen solving methods are based on scientific criteria.

The present study, however, is based on the literature provided by three databases and only deals with English written documents. The network provided by the software points out only 7 of 55 papers as significantly representative in the area. This number can be too modest to represent the whole area, and as a future research possibility, a more extended in-depth analysis can be performed.

Acknowledgments This research was supported by the German Research Foundation (DFG) and the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES) as part of the BRAGECRIM project “Integrating Intelligent Maintenance Systems and Spare Parts Supply Chains (I2MS2C)” (BRAGECRIM 022/2012).

3. ON THE RESEARCH OF LINEAR PROGRAMMING SOLVING METHODS FOR NON-HIERARCHICAL SPARE PARTS SUPPLY CHAIN PLANNING

As could be concluded from the analysis of the works on collaboration and supply chain planning, the majority show a lack of decision support information for choosing the most efficient solving method for a given scenario. The present chapter aims to facilitate the choice of the most appropriate solving method by building a table of characteristics of the most used solving methods in the literature, which is accomplished through a literature review.

3.1. INTRODUCTION

Specific requirements must be taken into account when dealing with spare parts. First, a high service level is essential. The value of certain parts used in the industry is usually too high to keep them stored close to the production facilities. Concomitantly, breakdown times in the industry can be very harmful to a company's productivity. One of the most important aspects in an SPSC is having the production facilities as final customers, which implies in a higher cost when not attending the demand, as this will not be the only opportunity cost. According to Huiskonen (2001), material and time buffers in production systems are decreasing, generating even more pressure for efficiency in spare parts logistics.

The complexity of spare parts supply chains increases when dealing with the task of forecasting. According to Espíndola et al. (2012), the demand for spare parts is sporadic and urgent. To tackle this challenge, the authors have introduced the concept of integrating intelligent maintenance systems and spare parts supply chains, wherein sensors give real-time evaluation of the elements status in the industry and estimate the prediction of failures, making the forecasting deterministic and simplifying SPSC planning.

According to Dudek and Stadtler (2005), collaborative planning is the coordination process of autonomous yet interconnected Master Planning activities. Küppers (2013) classified 26 state-of-the-art collaborative planning concepts. As it can be seen in

Figure 12, where LP stands for Linear Programs, and Others means other methods of decision support models, LPs are the most common decision model for non-hierarchical supply chain planning.

Figure 12 - Occurrence of decision model type

Source: Küppers (2013), adapted by the author

In this chapter, methods to solve linear programing problems will be evaluated considering their capability of dealing with the most common decision model types associated with spare parts supply chains, applying collaborative planning concepts. The chapter is structured as follows. In section 3.2, a review of the basic concepts that support the present work is provided. In section 3.3, the main aspects of the principal solving methods are reviewed. In section 3.4, a discussion on how to fit the solving method with the requirements of collaborative spare parts supply chains is presented.

3.2. LITERATURE REVIEW

3.2.1. Spare Parts Supply Chain

When dealing with spare parts, high service levels are required due to the necessity of always having the right part at the right time. However, several aspects can make this task more complicated than usual, such as the high volume to be managed, the high responsibility required due to customer downtime costs, and the risk of obsolete inventory. In addition to these problems, Espíndola et al. (2012) also mention that, "due to the high costs for spare parts and their sporadic demand, keeping inventories of all parts at all warehouses in the spare parts network are not economical". Supply Chains are characterized by distinct, yet mutually interdependent decision domains with independent business objectives. In this way, the existing models' capability of supporting an intelligent and flexible synchronization and coordination of the involved process is limited. Given these intertwined and complex aspects, management processes of SPSCs cover different areas of knowledge, which, in turn, use various resources, methods, and techniques for solving coordination problems.

Some features of SPSCs are highlighted in the literature. First, the demand for spare parts usually has an intermittent and/or erratic behavior, making it more difficult to be forecast by classical statistical methods and inventory control (BOYLAN and SYNTETOS, 2010). The second aspect relates to high levels of required services. Components for maintenance need to be available as soon as a fault occurs, otherwise the productive systems may be inoperable, causing high costs for their companies (HUISKONEN, 2001). Another feature derives from the two previous characteristics; as there is a wide variation in demand and a network of well-lined stocks, distribution costs are high. In periods of low demand, inventories are still needed for periods of high demand, increasing the costs of distribution processes (FRAZZON et al., 2014).

As can be seen from these concepts, a detailed planning of the spare parts supply chains is necessary in order to meet service levels while minimizing costs. Furthermore, not only the planning but also the coordination between the different domains can be seen as a relevant topic, considering the autonomy of the different actors involved in the supply chain coordination. Collaboration can be reached through the exchange of relevant data from multiple individual planning domains (e.g. demand planning, master planning, production planning, etc.), aiming to design a collaborative planning concept. However, the applicability of existing CP approaches for coordinating the different autonomous actors in non-hierarchical SPSCs has not yet been investigated (ESPÍNDOLA et al., 2012). The portability of CP approaches to other scenarios, especially to an SPSC scenario, is still an open research issue.

3.2.2. Collaborative Planning

The integration of processes and activities related to supply logistics is an important requirement to improve cost management and services, usually aiming to enhance competitiveness. Also, a large part of a company’s performance can be attributed to production and logistic activities. Kopczak and Johnson (2003) explored important aspects of the integrated management of logistics processes and their effects on business competitiveness and the creation of value. According to the authors, ongoing changes are forcing companies to re-examine their business vision and redefine on which processes they focus their resources and skills.

In addition to this, the resulting interorganizational network consists of several autonomous companies, which cannot necessarily be forced to go along with the decisions, strategies or plans of a leader unit. Thus, "the effective and efficient management and hence coordination of such SCs cannot be achieved in the same way as in hierarchical organizations which can be controlled by one dominant actor" (HELLINGRATH and KÜPPERS, 2011b). The main problem is to equate the material and information flows that run throughout the supply chain. In other words, the better known and monitored these flows are, the lower the necessity will be for safety stocks to attend demand and production requirements (FERROZZI et al., 1993; CHRISTOPHER, 1997). This means that the less information the company has, or the poorer the information flows are, the more necessary the safety elements will be to meet the fluctuations in demand, which brings direct impact on the organization's profit margins. The lack of decisional and organizational integration leads to inefficiencies related to poor coordination of production and distribution decisions, resulting in missed opportunities, delays, inefficient inventory decisions, poor capacity allocation, and misuse of resources, all leading to the increase of costs (CHEN and LEE, 2004).

Collaborative planning concepts address these necessities by avoiding centralized planning or decision-making components and relying on coordination based on mutual agreement, without the exposure of the companies' private information and loss of local decision autonomy (HELLINGRATH and KÜPPERS, 2011b). Thus, CP can be defined as a "joint decision-making process for aligning plans of individual SC members with the aim of achieving coordination" (STADTLER, 2009). Therefore, "two or more chain members working together to create a competitive advantage through sharing information, making joint decisions, and share benefits, can result in a greater profitability of satisfying end customer needs, when compared to act alone" (SIMATUPANG and SRIDHARAN, 2002).

Different approaches to decentralized coordination by CP have been developed (DUDEK, 2009; HEGMANNS, 2010; STADTLER, 2009). Basically, these approaches share several characteristics, as this interorganizational planning process depends on the object of coordination (e.g. collaborative production planning) and the SC structure intended to be supported (e.g. multi-tier, build-to-order production and logistics networks). On the organization and management level, for example, the CP approach improves the flexibility and robustness of a company's structure and the transport system's efficiency.

In summary, this approach has the goal of achieving more sophisticated SC coordination mechanisms, regarding their better applicability in today's complex production systems, and respecting the autonomy of SC actors. In addition, according to Espíndola et al. (2012), this kind of coordination intends to overcome the restrictions of traditional hierarchical planning concepts regarding the practical applicability in today's supply chains, while simultaneously improving supply chain costs and/or performance.

3.2.3. Linear Programming

As it is possible to see in Hillier and Lieberman (2010), Linear Programming Models are mathematical optimization models formed by a linear objective function and m linear constraints. They can be generically written as:

$$Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n \qquad (1)$$

Subject to:

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1 \qquad (2)$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq b_2 \qquad (3)$$

$$\ldots$$

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq b_m \qquad (4)$$

And:

$$x_1, x_2, \ldots, x_n \geq 0 \qquad (5)$$

Linear programming models are widely used in the planning of optimization in supply chain and logistics areas. As can be observed in

Figure 12, LP models are the most frequently used in the state-of-the-art compendium of collaborative planning models. For this reason, LP will be the object of study of the present work.

3.2.4. Optimization Methods

According to the research presented by Griffis et al. (2012), optimization has been the preferred method to model and solve complex supply chain problems over the last decade. Optimization methods are one of the three main analytical methods for solving different problems, besides simulation and heuristics (GRIFFIS et al., 2012; BALLOU, 1989). For Coppin (2004), metaheuristics approaches are often considered part of the evolutionary or artificial intelligence class of the optimization methods. In this work, metaheuristics are going to be considered part of the optimization branch of the analytical methods. In agreement with Coppin's (2004) characterization, it can be noted that metaheuristics are being used to find solutions for complex cases of mathematical programming, as in the case of supply chain optimizations. For Ballou (1989), optimization is potentially the ideal method for solving decision problems because of its well-known procedures and the guarantee of finding an optimal solution. This, of course, is not entirely true, given that the concept of metaheuristics was introduced and classified as an optimization method for their characteristic of not providing the best possible solution. However, it is still convenient to classify metaheuristics as optimization methods, for they are being used as exact optimization methods to solve linear and nonlinear mathematical models. The classic exact optimization methods that Ballou (1989) was referring to indeed provide the best possible solutions. However, as Griffis et al. (2012) affirm, many logistics and supply chain problems are too large or too complex for the classic exact optimization methods to guarantee an optimal solution in a feasible time, while metaheuristics have the ability to deliver "near-optimal" solutions in reasonable running times.

The present work gathers characteristics from classic exact optimization methods and most used classic metaheuristics, as seen in Griffis et al. (2012), to support the decision of researchers in choosing the best fitting optimization method for solving linear programming models, often used to optimize non-hierarchical collaborative supply chains on their production and distribution planning.

3.3. SOLVING METHODS

In this section, a brief introduction is presented on the most classical exact methods, according to Hillier and Lieberman (2010), and the most frequent metaheuristics used in supply chain problem-solving, according to Griffis et al. (2012).

3.3.1. Simplex

Simplex is an algebraic procedure method largely used to solve linear programming problems. Due to its geometric concepts, the solution provided by the method is guaranteed to be optimal (HILLIER and LIEBERMAN, 2010). According to Hillier and Lieberman (2010), simplex is widely used today by researchers and, even though it is an exact method, it has an amazing capacity for solving big linear problems, being able to solve problems of the dimension of hundreds of thousands functional constraints in a reasonable time. Its running time is considered exponential and considered roughly proportional to the cube of the number of ordinary functional constraints.

One of the main advantages of the simplex method is that it is already implemented in most of today's solving software, leaving the interested researcher only with the task of modeling the problem. This can represent a great decrease in the implementation time.

3.3.2. Interior point

The discovery of the interior point systematic is considered by Hillier and Lieberman (2010) as the biggest advance of the operational research field in the 80s. This method brought some advantages in comparison to simplex, mostly because of its capacity to solve problems within reasonable times beyond the capacity of simplex. Currently, the most advanced problem-solving software has at least one interior point algorithm implemented in parallel with simplex.

According to Hillier and Lieberman (2010), the interior point method has, therefore, more complex concepts, making its implementation more exhausting in case the researcher wants to implement it by himself. The method also requires more exhaustive iterations, which can make it slower than simplex when dealing with smaller problems.

The interior point's execution time is proven to be polynomial. This characteristic can barely be noticed when applying the method to most routine problems. However, the interior point method presents an advantage when dealing with colossal problems of the order of millions of constraints, as the number of iterations required to solve big problems does not increase proportionally to the number of constraints and decision variables (HILLIER and LIEBERMAN, 2010).

3.3.3. Genetic algorithm

Often considered one of the most famous metaheuristics approaches, the Genetic Algorithm (GA) is inspired by the biological behavior of genetic evolution to solve combinatorial problems. According to Griffis et al. (2012), one of the method's advantages is not requiring an extensive knowledge about the constraints and rules of the problem. Besides, like other metaheuristics, it does not need a linear formulation. For Gendreau and Potvin (2010), it also has the feature of quick convergence. Like other metaheuristics, the Genetic Algorithm does not guarantee an optimal solution. The GA has a plus on its implementation complexity: the fitness function. According to Dréo (2006), the design of the crossing over method to generate new offspring can be rather difficult to implement.

Farahani and Elahipanah (2008) utilized the Genetic Algorithm to optimize total cost and service level for a just-in-time distribution in a supply chain, a mixed-integer linear programming model. Chan et al. (2005) allocated jobs into suitable production plants by using a GA to solve a linear programming model.

3.3.4. Tabu Search

Tabu Search is a metaheuristic method that can be simply defined as a search procedure for good solutions powered by a long-term memory for the current optimum and a short memory to avoid retroceding in the movement. According to Gendreau and Potvin (2010), some works even allow non-feasible solutions. For Griffis et al. (2012), the real advantage of the Tabu Search is the ability of auto-adjusting the parameters to direct the search towards an optimal solution. The authors also affirm that the development of new algorithms for this search method is still in rise in the literature.

Gendreau and Potvin (2010) define the method as one of the most effective, if not the best, for solving complex problems and affirm that it provides results that are very close to optimal solutions. The drawbacks of the Tabu Search concern its implementation. Cordeau et al. (2002) warn about its complexity and limited flexibility of coding. Gendreau et al. (2010) say that it is very common to see failed implementations of the search, generally for two main reasons: insufficient understanding of the fundamental concepts of the method and insufficient understanding of the problem at hand.

Khalaf et al. (2011) defined an optimal bill of material in a supply chain using the Tabu Search to find a good solution for a mixed integer linear program model. Melo et al. (2012) redesigned a multi-echelon supply chain network over a planning horizon by modeling it as a mixed integer linear program and obtaining the solution with the Tabu Search method.

3.3.5. Simulated Annealing

According to Gendreau and Potvin (2010), simulated annealing is a local search metaheuristic with the main ability of escaping the local optima. Among other features, the most important are its finite-time behavior and its asymptotic convergence. It is used mostly in discrete problems, but it can also be applied to continuous problems. Gendreau and Potvin (2010) affirm that one of the disadvantages of the simulated annealing is its frequent requirement of extensive computer time.

As seen in Gendreau and Potvin (2010), it is possible to conclude that simulated annealing is giving way to new algorithms. It was, in general, popular for its simplicity, easy implementation, local optimal avoidance, finite-time behavior and asymptotic convergence, but new algorithms are trying to overcome its disadvantage of requiring a long computer running time when compared to other metaheuristic models.

Jayaraman and Ross (2003) applied the simulated annealing methodology to optimize a mixed integer linear program model for production, logistics, outbound, and transportation planning. Balaji and Jawahar (2010) used simulated annealing in a two-stage distribution problem of a supply chain.

3.3.6. Ant Colony Optimization

Ant Colony Optimization (ACO) is a metaheuristic approach that imitates the behavior of ants laying pheromone trails to guide other ants. Gendreau and Potvin (2010) affirm that ACO is a well-established metaheuristic that attracts a large number of researchers aiming to solve computationally challenging problems.

For Griffis et al. (2012), ACO has distinct advantages and disadvantages. One of its positive aspects is that ACO can fit very well with any problem that can be formulated analogously to a routing or traveling salesman problem. In addition to this, ACO effectively compiles the data of trails and routes previously explored, which, according to Griffis et al. (2012), makes it a good approach for the dynamic problems of supply chains. On the other hand, the method can require a great amount of time for the establishment of several parameters. In addition to this, keeping the pheromone trails database updated can make the coding process challenging.

Ding et al. (2012) developed an improved ant colony approach to be applied in vehicle routing problems with time windows. Calvete et al. (2011) used ant colony optimization to solve a bi-level model for production-distribution.

3.4. DISCUSSION

Table 4 shows an overview of the main characteristics of each approach considered in this work. All methods presented in the literature review were selected for their feasibility of application in linear programming problems, which initially makes all the approaches possible choices for solving linear models. It is easy to notice that there is a lack of technical criteria to guide the selection of the most appropriate method. An approach selection is a choice that must also consider subjective criteria, as the experience of the researcher on its implementation. To simplify the selection procedure, the methods can be initially divided into two groups: algebraic methods and metaheuristics.

As discussed in the literature review, the main characteristic of the problem to be solved is its dimension. Metaheuristics have the ability to deal with any problem of large dimensions within a reasonable execution time but their distance from the optimal solution can represent a great loss in a real application. Results can be satisfying sometimes but only when no better solution is possible to be reached. Exact methods have limits regarding the problem size, but according to the literature, they are still able to deal with problems of more than one hundred thousand constraints and even more decision variables, which can make them suitable for a huge number of routine problems. Thus, when not dealing with problems with less than a million constraints, it is still more attractive to work with methods that guarantee optimal solutions. If the problem is large enough to justify using metaheuristics, the choice process resumes in identifying the main characteristics of the problem, the interesting individual characteristics and the implementation skills. If the problem is not large enough, then the decision should consider its size and the available software. If the size of the problem is close to the limit in which metaheuristics is needed, then the interior point method can be a better choice. On the other hand, if the size of the problem is approximate to the ones frequently found, with less than one hundred thousand functional constraints, then choosing simplex can be a better idea, due to its availability and processing time in this dimension.

Table 4 - Summary of the approaches' characteristics and recommendations

	ACO	Simulated Annealing	Tabu Search	Genetic Algorithm	Interior Point	Simplex
Problem size (constraints)	Any	Any	Any	Any	Up to 1 million	Up to 500.000
Execution Time	Low	Low/Medium	Low	Low	Medium	Medium
Implementation Complexity	Complex	Easy	Complex	Normal	Normal	Easy
Optimal guaranteed	No	No	No	No	Yes	Yes
Advantages	Keeps data on previous trails.	Finite time behavior, asymptotic convergence.	Self-adjusting parameters. Considered one of the most effective methods.	Requires little knowledge of the constraints and rules of the problem. Quick convergence.	Lower execution time in the exact methods.	Already implemented in most of the solution software.
Disadvantages	Defining parameters can require a considerable amount of time.	Extensive execution time when compared to other metaheuristics.	Frequent failed application due to complexity on implementation.	Complexity on the implementation of new offspring generation.	Less often implemented. Slower than simplex for small/medium problems.	Lower capacity of dealing with big problems.

Source: Author

3.5. CONCLUSIONS

Non-hierarchical supply chain research is a necessary and growing area for supply chain planning application in real cases. Its concept can make the application of supply chain optimization attractive for all the actors of the SC.

For non-hierarchical SCs, linear programming is the most frequent type of mathematical modeling employed. There is a large variety of methods for solving linear programming problems, few exact methods and a growing number of metaheuristics. In this work, it was possible to verify that the main criterion for choosing the optimization approach is the problem size. Metaheuristics are normally necessary when the problem is too large for applying exact methods. With the exception of these cases, metaheuristic approaches are usually less attractive due to their complexity of implementation as they do not guarantee an optimal solution. In relation to the exact methods, the interior point method is more adequate for solving problems with larger dimensions, due to the lower execution time at this level, but when dealing with smaller problems, simplex can be a better choice for its availability. Taking into account these characteristics can lead to a more efficient application of decentralized collaborative planning in spare parts supply chains integrated to intelligent maintenance systems.

However, the present work must be read under light of some restrictions. The work only considers the most classical methods, thus, there are other methods that can be applied to solve linear programs that were not discussed herein. The characteristics taken into account were also subjective in a certain manner, and an empirical study applying these methods to solve a single problem is needed to confirm the expected aspects.

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4. COLLABORATIVE OPERATIONAL PLANNING FOR DECENTRALIZED SPARE PARTS SUPPLY CHAINS

This section aims to bridge the gap identified in the second chapter with the development of a procedure to apply a decentralized supply chain planning in a collaborative spare parts supply chain using the most suitable solving method presented in the third chapter.

The model chosen for solving the test case is a linear programming problem, as expected. As the test case depicts a problem with less than one thousand constraints and fewer variables, according to the last section, simplex should be the most suitable solving method, since it can guarantee an optimal solution in a very small amount of time. The software CPLEX was used to obtain the solution, and the implemented code is presented in Appendix A.

4.1. INTRODUCTION

Modern business management faces the challenge of individual businesses no longer competing as solely autonomous entities but rather as supply chains (LAMBERT and COOPER, 2000). Thus, supply chain management is considered to involve integration, coordination, and collaboration across organizations and throughout the supply chain (STANK et al., 2001). Collaboration in the supply chain comes in a wide range of forms but, in general, has a common goal: to create a transparent, visible demand pattern that paces the entire supply chain (HOLWEG et al., 2005). Ireland and Webb (2007) highlight that the challenging nature of competing in a global environment creates several tension-filled questions for today’s firms, for example: in what markets should the company compete? How much risk is the company willing to accept to compete in markets with which they are not deeply familiar? What kinds of skills should the company develop in order to become more innovative? Added to this, in the particular case of SPSCs, several aspects make the task of providing spare parts and maintenance services challenging, as the high number of parts to be managed, sporadic demand, high responsibility required due to customer downtime cost, risk of obsolete inventory, among others (ESPÍNDOLA, 2012). Israel (2016) affirms that proper maintenance and availability of the needed spare parts directly influence the production systems’ effectiveness and efficiency.

According to Stadtler (2009), “one important way to achieve coordination in an interorganizational SC is the alignment of future activities of SC members, hence the coordination of plans". Therefore, a collaborative SC strategy recognizes that integrated business processes create value for the customers. Several supply chain elements, namely strategies/policies/processes, structure, relationships, and coordination/control have been utilized to discuss spare parts management in the context of supply chain development. Huiskonen (2001) argues that the only way to bring the conflicting views of suppliers and customers into alignment is through the collaborative design of the logistical network structure as a whole. The author also emphasizes the importance of information exchange at an early stage, particularly in multi-echelon inventory systems where "control and coordination in interorganizational settings need not always be based on hard formal systems but are often achieved by 'soft' means through trust and commitment between the parties".

In this context, this chapter aims to propose a structured procedure for fitting an operational planning concept to the collaboration specificities of spare parts supply chains as well as its application. The chapter is structured into three main sections. Section 4.2 presents a literature review on the topic. In the sequence, a procedure for the decentralized collaborative planning application in spare parts supply chains is presented. Section 4.4 details the test case and presents the exemplary application, including obtained results and analysis. Finally, the chapter is wrapped up with concluding remarks regarding its managerial and scientific impact.

4.2. LITERATURE REVIEW

The following sections present an overview of specific spare parts supply chain coordination research areas that provide the theoretical foundation for the current research.

4.2.1. Spare Parts Supply Chain

Spare parts must be available in the right place within the supply chain to ensure the desired level of service. However, several aspects make this task complicated, such as the high number of parts to be managed, high responsibility required due to customer downtime costs, and the risk of obsolete inventory. According to Espíndola et al. (2012), "due to the high costs for spare parts and their sporadic demand, keeping inventories of all parts at all warehouses in the spare parts network is not economical". In addition, supply chains are thus characterized by distinct, yet mutually interdependent decision domains with independent business objectives. Therefore, the capability of existing models of supporting an intelligent and flexible synchronization and coordination of the involved processes is limited. Given these intertwined and complex aspects, management processes of spare parts supply chains cover different areas of knowledge, which, in turn, use various resources, methods, and techniques for solving coordination problems.

Some features of SPSCs are highlighted in the literature. First, the demand for spare parts usually has an intermittent and/or erratic character, making the forecasting process by classical statistical methods and inventory control more difficult (BOYLAN and SYNTETOS, 2010). The second characteristic relates to the high levels of required services. Components for maintenance must be available as soon as a fault occurs, otherwise the productive systems may be inoperable, causing high costs for their companies (HUISKONEN, 2001). Another feature derives from the two previous characteristics; as there is a wide variation in demand and a network of well-lined stocks, distribution costs are high. In periods of low demand, inventories are still needed for periods of high demand, increasing the costs of distribution processes (ISRAEL, 2014).

Having seen these concepts, a detailed planning of spare parts supply chains is required in order to meet service levels while minimizing costs. Furthermore, not only planning but also coordination between different domains can be seen as a relevant topic, considering the autonomy of the different actors involved in supply chain coordination. Collaboration can be reached through the exchange of relevant data from multiple individual planning domains (e.g. demand planning, master planning, production planning, etc.), aiming to design a collaborative planning concept. However, the applicability of existing CP approaches for coordinating the different autonomous actors in heterarchical SPSCs has not yet been investigated (ESPÍNDOLA et al., 2012). The portability of CP approaches to other scenarios, especially to an SPSC scenario, is still an open research issue.

The study developed in this paper is based on the real case of a reference company in the production and distribution of spare parts for electric actuators in Brazil, which will be described hereafter.

4.2.2. Supply Chain Coordination

The integration of supply chain actors, including their processes and activities, related to supply, production, and distribution logistics, is an important prerequisite for cost and services management. The integration usually aims at enhancing the competitiveness of the supply chain, but the performance of the individual companies also relies on different activities performed by distributed actors. Kopczak and Johnson (2003) explored important aspects of the integrated management of logistics processes and their effects on business competitiveness and the creation of value. According to the authors, ongoing changes were forcing companies to re-examine their business vision and redefine on which processes they focus their resources and skills. Moreover, the resulting interorganizational network consists of several autonomous companies that cannot necessarily be forced to follow the decisions, strategies or plans of a superordinate unit. Thus, "the effective and efficient management and hence coordination of such supply chains cannot be achieved in the same way as in hierarchical organizations which can be controlled by one dominant actor" (HELLINGRATH and KÜPPERS, 2011a).

The main problem is balancing material and information flows throughout the supply chain. Usually, comparatively high safety stocks are kept in spare parts supply chains in order to cope with demand uncertainties and production requirements, which has a direct impact on the companies' profit margins. However, the better the exchange of information between the actors and the better the quality of information each actor has, the lower the need for safety stocks within the supply chain (FERROZZI et al., 1993; CHRISTOPHER, 1997). This lack of decisional and organizational integration leads to inefficiencies related to poor coordination of production and distribution decisions and further results in missed opportunities, delays, inefficient inventory decisions, poor capacity allocation, and misuse of resources, all leading to increased costs (LEE et al., 2004).

Frayret (2009) mentions that the problem "consists in synchronizing the supply chain partners' usage of their resources in order to avoid shortage and make sure materials, components and final products flow continuously whenever needed by downstream partners, at minimal cost". Thus, decisions such as what and when to produce and deliver become crucial points in business strategies. The author also highlights that an important feature of this coordination issue is its distributed nature, for the companies have different processes, decisions, and strategies in the supply chain. Consequently, in general, they can make any decision and follow any decision process they want. Moreover, companies are often not just part of one but of several different supply chains at the same time. Each company needs to balance its commitments within the supply chains that it is part of and has to plan its own business functions (CALISUSCO et al., 2004). Thus, the most challenging aspect of this problem is to provide a solution that meets this distributed nature.

A traditional planning model for hierarchical supply chains can, therefore, either describe only a part of a distributed supply chain, a single given actor or encompass all links of all actors in a supply chain, which is infeasible in today's complex production networks. Moreover, the supply chain actors are often unwilling to share strategic or sensible information, e.g. production capabilities or resources, and do not want to give up their local decision autonomy (BREITER et al., 2009). Hence, the various actors of heterarchical supply chains need to be coordinated differently, while the internal planning of a single actor can be organized hierarchically (DUDEK, 2009). The planning of heterarchical structures is often done in succession throughout the different tiers. Each supply chain actor uses the inputs of the preceding tier to plan its business function and provides the calculated demands to its suppliers (HELLINGRATH and BÖHLE, 2010). Breiter (2009) presents several approaches for heterarchical coordination:

- Central collaborative planning: A central trusted organization facilitates the coordination of the actors by receiving private information from all actors. In addition, the trusted organization is legitimized to make decisions for the entire supply chain.
- Mathematic decomposition: The global supply chain planning model for all business functions is split into smaller sub-problems for the local planning of each actor. The sub-problems are solved separately but must be coordinated via a superior level in order to find a solution for the entire supply chain.
- Hierarchic anticipation: The decision-making process is distinguished between a top and a base level. First, the top level

makes its decisions, and this influences the decisions made on the base level. The top level also anticipates the reactions of the base level with the goal of increasing the coordination between both levels.

- Self-selection: This form of coordination is contract-based and considers especially the aspect of information asymmetry. Actors that have less power to enforce decisions develop a set of different options. The other actors can then choose from the presented options.
- Automatized negotiations: A mutually accepted agreement is achieved by an iterative execution between the actors. It provides the basis for heuristic-based concepts that rely, in large part, on negotiation processes.

However, all presented approaches have individual shortcomings. They either rely on the implementation of a central decision-making authority, the exchange of private information, asymmetric power interactions or are still only of theoretic nature (KÜPPERS et al. 2015). Hence, research in the field of collaborative planning addresses the special characteristics of coordinating heterarchical supply chains. Collaborative planning concepts explicitly consider the aspects and peculiarities of heterarchical supply chains and are regarded as promising solutions to improve their effectiveness (DUDEK, 2009).

4.2.3. Collaborative planning

Collaborative planning concepts address the necessities of heterarchical supply chains by avoiding centralized planning or decision-making components. Furthermore, they provide mutual agreement-based coordination without the disclosure of the companies' private information or loss of local decision autonomy (HELLINGRATH and KÜPPERS, 2011a). CP can be defined as a "joint decision-making process for aligning plans of individual SC members with the aim of achieving coordination" (STADTLER, 2009). Thus, "two or more chain members working together to create a competitive advantage through sharing information, making joint decisions, and share benefits, can result in a greater profitability of satisfying end customer needs, when compared to act alone" (SIMATUPANG and SRIDHARAN, 2002).

Different studies on decentralized supply chain coordination by CP have been developed, e.g. Dudek (2009); Hegmanns (2010); Breiter et al. (2009); Stadtler (2009). These approaches share several characteristics. For example, the interorganizational planning process depends on the object of coordination (e.g. collaborative production planning) and the supply chain structure that is intended to be supported (e.g. multi-tier, build-to-order production and logistics networks). On the organization and management level, CP helps to increase the flexibility, robustness, and efficiency of a supply chain. In general, a typical CP process consists of six underlying steps that are performed in a continuous succession (STADTLER et al., 2015):

- Definition: First, the scope of collaboration activities and CP need to be defined in a so-called collaboration agreement. This contract specifies the products or services to be coordinated, the time horizon as well as the coordination processes.
- Local domain planning: Each actor creates a set of different local plans on its own and ranks them by preference. The plan describes the solution for a local planning situation, for example a production plan, and forms the basis for communicating with the other actors.
- Plan exchange: The previously agreed-on information on the local plans is exchanged between the actors in order to facilitate the understanding of the coordination situation.
- Negotiation and exception handling: This iterative step aims to find a solution for the planning problem of each bilateral customer and supplier relation within the supply chain. The suppliers evaluate the proposals received from their customers to determine their preferred supply plans. Then, these plans can be evaluated by the customers. The negotiation of compromises and possible compensation payments is conducted until an agreement is reached. In case of exceptional situations, e.g. production capacity overload, predefined rules are applied that specify how to address these planning problems.
- Execution: After a plan has been accepted within the supply chain, the resulting replenishment, production and purchasing processes of the actors are executed.
- Performance measurement: This step measures the effects of collaboration on the performance of the supply chain and checks if the desired outcomes were reached.

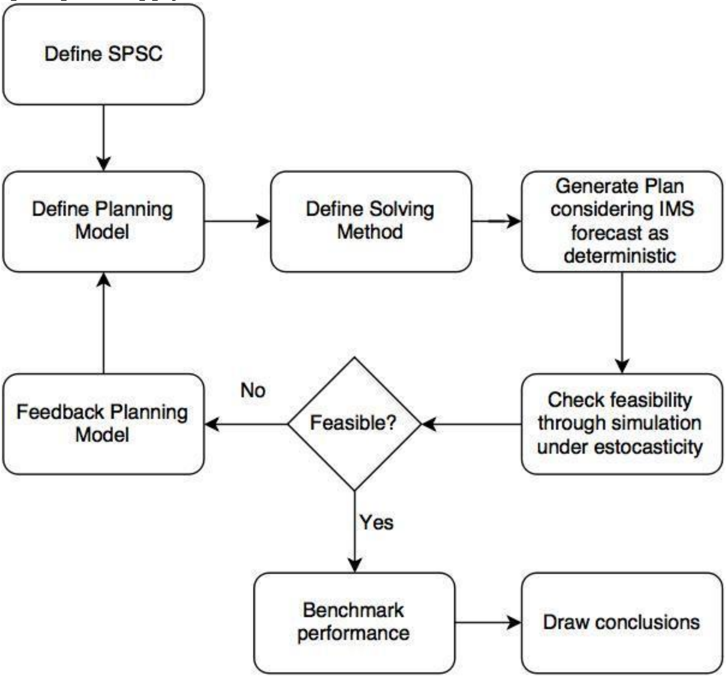
In summary, CP has the goal of achieving more sophisticated supply chain coordination mechanisms, regarding their better applicability in today's complex production systems, and respecting the autonomy of the supply chain actors. Espíndola et al. (2012) highlight that CP intends to overcome the restrictions of traditional hierarchical planning concepts regarding the practical applicability in today's supply chains, while simultaneously improving supply chain cost and/or performance. Hence, the effects of introducing CP to a specific supply chain must be estimated. In general, there is a range of different CP concepts presented in the literature. Therefore, guidance and tool support are required for the identification of applicable CP concepts for a specific coordination problem as well as the means to assess their expected performance (KÜPPERS, 2013). In this chapter, a collaborative planning model will be proposed for a specific spare parts supply chain of a Brazilian electric manufacturing company.

4.3. A PROCEDURE TO DECENTRALIZED COLLABORATIVE PLANNING IN SPARE PARTS SUPPLY CHAINS

In the present section, a procedure to apply a decentralized collaborative planning model to a spare parts supply chain integrated to intelligent maintenance systems will be proposed. The procedure is illustrated in Figure 13.

The first step is to define the spare parts supply chain to be applied. There must be plenty of knowledge available on the SPSC since each step will require a significant amount of information in order to be applied. The information required will depend on the result of each step (for example, different planning models defined in the second step will require different types of information).

Figure 13 - A procedure for decentralized collaborative planning application in spare parts supply chains

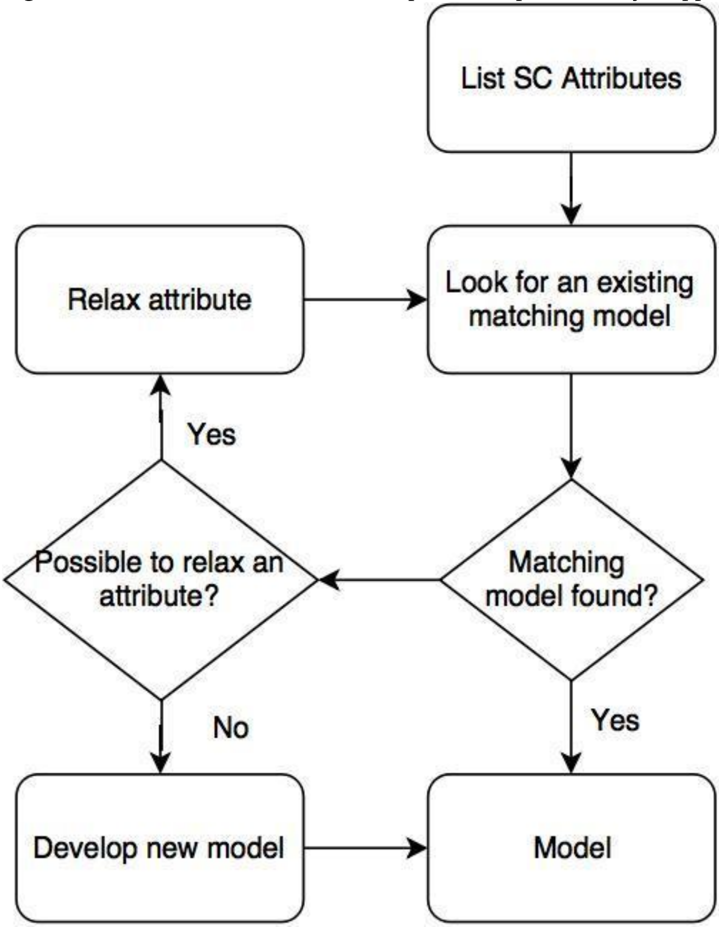


Source: Author

In the second step, a planning model shall be defined, but first, a systematic procedure, the Framework for Intelligent Supply Chain Operations (FRISCO) assessment approach, will be applied as proposed by Küppers et al. (2015). This procedure starts by specifying a list of attribute values that represent the main supply chain's characteristics. Afterward, the goal is to find an existing collaborative planning concept that matches the spare parts supply chain. Therefore, each of the attribute values is compared to an existing library of classified collaborative planning concepts presented in Küppers (2013). If there is no perfect match, attribute values are to be relaxed in a given order. If even after the relaxation there is no match, a specific collaborative planning concept should be developed for the studied SPSC. Finally, the optimization of the resulting collaborative model is proposed by using hybrid approaches that aim to combine the advantages of analytical methods, such as linear programming, and simulation models that are able to consider the detailed structure and behavior of the system, including dynamic environments and perturbations.

The mentioned search procedure was presented by Küppers et al. (2015) and it consists in an approach for designing solutions for coordination problems, which allows the use of partial or the entire reuse of existing CP-based solutions. This procedure is illustrated in Figure 14.

Figure 14 - Decentralized model search procedure presented by Küppers (2015)



Source: Author

The third step explores an efficient solving approach to support the defined model execution. The choice will depend on the model outputted from step 2. However, 18 of the 26 models listed in the state-of-the-art concept library by Küppers (2013) are modeled as Linear Programming problems, which can be solved using the metaheuristics or algebraic approaches. Thus, the choice will depend on the size of the SPSC in question, its number of decision variables and the limitations of the available software.

Then, in the fifth step, the model can be executed and a plan can be generated considering the demands forecast by the IMS as deterministic values. Thus, in the next step, the feasibility of the generated plan shall be checked through simulation, as well as the performance of the model under an expected variability on the demand. In case of non-feasibility or bad performance under variability, the planning model must be feedback. Otherwise, the model can be considered feasible, and its performance can be compared to other management strategies in order to decide whether or not the model will be adopted.

4.4. APPLICATION

The case used for testing was taken and adapted from (Israel 2014) and is represented in Figure 15. It comprises a company with a factory and a Distribution Center located in the south of Brazil. The company, named Alpha on the original work and also in this one, provides three components of electrical actuators for mainly five markets in different Brazilian states (here decreased to four, due to the solving software limitations). The company also has three intermediate Service Centers (here reduced to two). This work will consider the flow of the three products manufactured by Alpha Company.

In the given supply chain, the number of tiers was listed as multiple as it consists of four actors: Production, Transporter, Warehouses, and Market. The number of actors on each tier is diverging since it has the proportion 1:1:3:5. The business functions are production and distribution; here transport and warehousing were considered part of distribution since storing or not would be a transport decision. The actors' power relationship is symmetric, because each agent is independent. The actors' behavior was considered teamlike. The compensation payments were listed as arbitrary since models of both types would fit the supply chain. The concession strategy was assumed greedy, due to the market characteristics. The decision model, as seen in Israel (2014), employs Linear Programming. Due to the use of Intelligent Maintenance Systems, planning with rolling horizons is possible. The initial solution is, according to Stadtler (2009), down-stream because the solution starts in the tier furthest from the final client. There are no mediators nor actor-relationship requirements. The main exchanged information is the demand information. There are no different levels of commitment during the coordination process, i.e. no negotiation states. The negotiation roles are proactive and the number of rounds arbitrary. The outcome list is shown in

Table 5.

After specifying the attributes' values, the matching procedure was started. Following the method proposed by Küppers et al. (2015) the goal is to find an existing model that matches all attributes, and if that is not possible, to relax some determined attributes in an order given by the method. If even after the relaxation there is no perfect match, a specific model should be developed for the present supply chain.

In the first round of comparison, with the model library of Küppers (2013), no perfect match was found.

Table 5 - Spare Parts Supply Chain attributes before and after relaxation

	Characteristic	Original		Relaxed/Matched

Structural	Number of tiers	Multiple	→	Two
	Number of actors on each tier	Diverging	→	Bilateral
	Business functions	Prod/dist (3PL)		Prod/dist (3PL)
Actor Relationship	Actors' power relationship	Symmetric		Symmetric
	Actors' behavior	Team		Team
	Compensation payments	Arbitrary		No
	Concession strategy	Greedy	→	Implicit concessions
Decision Situation	Coordination goal	Arbitrary		Cost minimization
	Decision model	LP		LP
	Rolling Horizons	Yes	→	No
	Initial Solution	Downstream		Downstream
Solution Attributes	Mediator	No		No
	Actor-relationship requirements	No		No
	Exchanged information	Demand		Demand
	Negotiation states	None		None
	Negotiation roles	Proactive		Proactive
	Number of rounds	Arbitrary		Multiple

Source: Author

The models that did not match the present supply chain in attributes and had no possibility of relaxation were discarded. The first relaxation was in the concession strategy, from Greedy to Implicit Concession, which still did not yield a perfect match. The second relaxation was in the rolling horizon planning, from yes to no. After this relaxation, every model left in the database differed from the studied supply chain on the number of supply chain tiers and number of actors on each tier. Relaxing these attributes yielded a perfect match. Then, the order was changed to keep as many original characteristics as possible. The number of tiers was changed to two. The number of actors on each tier was changed to two. Since the final relaxation only preserved production and distribution, the new ratio was 1:1, which makes the bilateral assumption true. The relaxed attributes can be seen in

Table 5.

The perfect match was obtained with the model proposed by Jung et al. (2008), which describes a form of distributor-driven supply chain negotiation model and consists of a supply chain where a distributor (named DA, or distribution agent) works and negotiates with a factory (named PA, or production agent). The optimization model consists of one distribution planning model for the distribution agent and one production planning model for the production agent (JUNG et al, 2008). The equations are presented in the sequence.

Table 6 - Decentralized Planning model by Jung (2008)

Planning model for Distribution Agent

$$Max \sum_{k,t,m} \left(p_{kmt} \sum_d y_{kdmt}\right) - \sum_{k,t} \left\{ \sum_{i \in N, j \in N} T_{kijt} y_{kijt} - \sum_d \hat{h}_{kdt} \hat{I}_{kdt} - \sum_f \left(w_{kft} \sum_d y_{kfdt}\right) \right\} \quad (9)$$

s.t.

$$\hat{I}_{kdt} + \sum_f y_{kfdt} - \sum_d y_{kdmt} = I_{kft+1} \quad \forall k,d,t \quad (10)$$

$$\sum_d y_{kdmt} \le D_{kmt} \quad \forall k,m,t \quad (11)$$

$$\sum_k v_k \hat{I}_{kdt} \le \hat{H}_{dt} \quad \forall d,t \quad (12)$$

$$\sum_k c_{kf} x_{kft} \le C_{ft} \quad \forall f,t \quad (13)$$

$$\hat{I}_{kdt}, y_{kijt} \ge 0 \ \forall k,d,i,j,t \quad (14)$$

Planning model for Production Agent

$$Max \sum_{k,f,t} \left(w_{kft}\left(O_{kft} - b_{kft}\right)\right) - \sum_{k,f,t} \left(r_{kft} x_{kft} + h_{kft} I_{kft}\right) \quad (15)$$

s.t.

$$I_{kft} + x_{kft} - \left(O_{kft} - b_{kft}\right) = I_{kft+1} \quad \forall k,f,t \quad (16)$$

$$\sum_k v_k I_{kft} \le H_{ft} \quad \forall f,t \quad (17)$$

$$\sum_k c_{kf} x_{kft} \le C_{ft} \quad \forall f,t \quad (18)$$

$$x_{kft}, I_{kft}, b_{kft} \ge 0 \ \forall k,f,d,i,j,t \quad (19)$$

Source: Author

Equation 9 defines the distribution agent's profit, while equation 10 represents the mass balance within the Distribution Centers. Equation 11 establishes a limit on the products' delivery to equal the demand of the markets. Equation 12 limits the capacity of the Distribution Centers' storage. Equation 13 limits the order of the DA in the aggregated capacity perceived by the DA, while equation 14 establishes non-negative variables. Equation 15 represents the PA's profit, while equation 16 defines the mass balance of the production facilities. Equation 17 limits the storage capacity of production facilities, while equation 18 restricts the amount to be produced by the production facilities at their capacities. Equation 19 establishes non-negative variables in the PA's model.

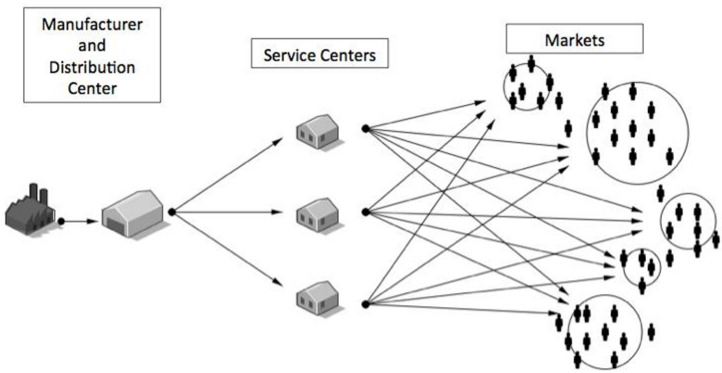
Finally, to solve the proposed model, hybrid approaches are recommended. Advanced mathematical modeling and algorithms to support decision-making provide a way to not only model supply chains with a collaborative planning but also to provide the means to solve complex decision problems and create efficient decision support systems. Thus, the first tool to be used in future studies to solve the proposed collaborative model is the mathematical optimization and operational research.

However, according to Frazzon et al. (2015), the analytical methods, such as linear programming, provide an optimal solution but do not fit properly with the reality characteristics. In addition, several studies (HUNG and LEACHMAN, 1996; BYRNE and BAKIR, 1999; KIM and KIM, 2001; and BYRNE and HOSSAIN, 2005) have combined simulation and mathematical programming models in an iterative scheme to evaluate the effects of the release decisions upon the performance of a manufacturing system. The simulation-based techniques can be used to either develop or evaluate complex systems. Aspects like the physical configuration or the operation rules of a system can be considered. Its applications have grown in all areas, assisting managers in the decision-making process and enabling a better understanding of processes in complex systems (SAKURADA and MIYAKE, 2009).

The integration of analytical models with simulation results in hybrid models, a challenging alternative that leads to better results. Therefore, hybrid models will be used to combine the advantages and avoid the disadvantages of both tools. According to Lee et al. (2002), the hybrid simulation–analytic approach consists in building independent analytic and simulation models of the system as a whole, developing their solution procedures, and combining their solution procedures for problem-solving.

The supply chain in which the methodology will be applied was presented in Israel (2014), and consists of a simplified spare parts supply chain with a production facility that manufactures three types of products (the more important ones) and has to attend, as the final destination, five big markets. The clients of this supply chain are industries that buy these products as spare parts for maintenance. Intelligent maintenance systems are used in this supply chain, which makes the demand foreseeable for each of the following fifteen days. The supply chain scheme is represented in Figure 15.

Figure 15 - Supply Chain Structure of Alfa Company



Source: Israel (2014)

Related to the data used in the test case, the demands of the three products in the four markets are presented on Israel (2014), without the fifth market. These values were considered for the optimization phase. In the tests executed by Zuccolotto et al. (2015), the forecast accuracy of the IMS reached 93%. On the simulation phase, variability was included in the demand to assess the performance of the model under stochasticity. Four scenarios were created, all of them assuming a triangular distribution for the demand of each product, each day. In the first, the maximum and minimum were set to ±5% of the forecast, in the second, third and fourth, ±10%, ±15% and ±25%, respectively.

The transport time is not considered in the above-mentioned mathematical model neither will it be considered in the simulation model. The test case will not consider the allotment problem, and the transport of the spare parts will be considered as continuous.

For product one, the production cost is 64.50 and the estimated production time is 6 minutes; for product two, 82.5 and 9 minutes; and for product three, 45 and 8 minutes. Since the prices were not provided due to different business models, they were generated assuming profit in each delivery for both agents as the products were transported through the cheapest route and stored for one day only. The profit margin of the production agent was assumed as 70%, considering only the production and storing costs. The profit of the distributor was assumed as 20%, considering the cost of acquisition, storage and transport. Thus, the wholesale price of the products one, two and three are 301, 385 and 210, respectively, and the market prices were assumed 2938, 3238.75 and 1766.25. The high market prices are justified due to the high transportation costs, a characteristic of the high service level (focusing on the short lead-time) required. The possibility of backlogging was not considered. The stock cost in the DC is 25.8 for product one, 33 and 18 for product two and three, and in the SCs 34.4, 44, 24 respectively. The transportation costs are presented in the following table.

Table 7 - Transportation costs

	F			SC1			SC2		
	1	2	3	1	2	3	1	2	3
SC1	1162	1486	810	-	-	-	-	-	-
SC2	755	966	527	-	-	-	-	-	-
M1	-	-	-	0	0	0	460	488	321
M2	-	-	-	312	396	216	215	225	150
M3	-	-	-	529	676	369	430	550	300
M4	-	-	-	475	605	330	264	335	183

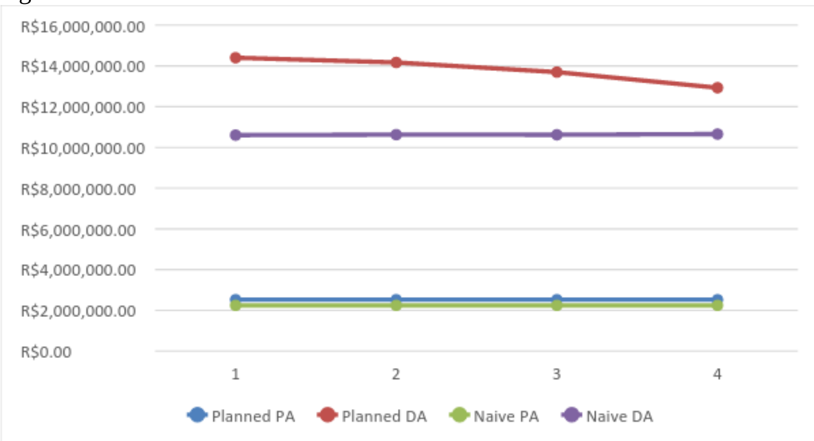
Source: Israel (2014)

The optimization models were implemented and executed on the software IBM ILOG CPLEX. The optimization is performed as follows: first, the DA model is executed considering that the PA has infinite capacity, then it generates its own plan and sends the orders to the PA agent; the PA agent executes its plan and sends back the shortage to the PA. The DA interprets the shortage and considers the production capacity proportionally lower, executes its plan again, and sends a new order to the PA agent. The procedure continues until there is no shortage reported by the PA (considering the order by the DA, not the actual demand in the market). In the present work, the algorithm converged in the fourth iteration, with a DA profit of 14 858 193.25 and PA profit of 2 526 549.00.

In order to compare the performance of the results given by the mathematical model, a simulation was created applying classical management strategies. The Naïve method was used to manage the SC's inventory. The method consists in keeping a safety inventory level, attending the maximum of the day's demand, and ordering the same amount attended in the day after. The markets are, at first, attended by the nearest (with cheapest transport) SC, and if this one cannot attend, then another will attend, if possible. The safety inventory level was calculated by the equation $SS = z \times \sigma_d \times \sqrt{l}$ with lead time equal to one (since the delivery is continuous and attended within a day) and z equal to three. This strategy is submitted to the same demand generated by the decentralized planning model.

In the second simulation model, the plan generated by the optimization model is used to manage the production facility and the service center's inventories. Both simulation models were created by the software AnyLogic. The results are presented in the figures below.

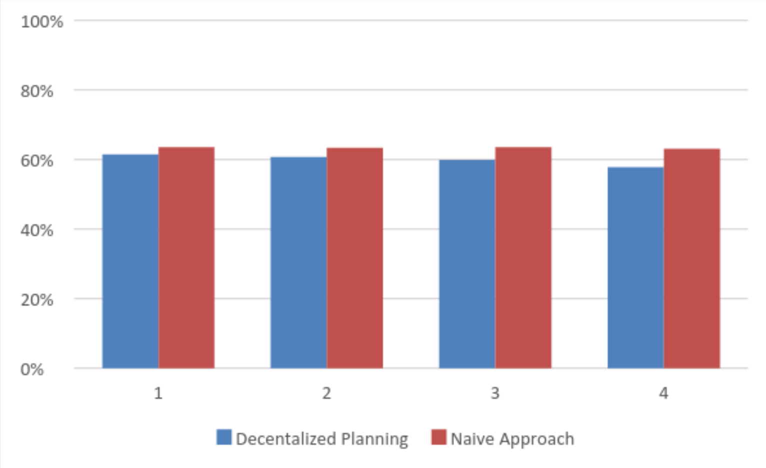
Figure 16 - Profits in the simulation model



Source: Author

As it is possible to see in Figure 16, the decentralized planning integrated with intelligent maintenance systems generates a bigger profit, mainly due to efficient ordering and inventory management. As expected, the efficiency of the decentralized planning decreases with the increase of uncertainty, but it was still better than the Naïve approach even at high uncertainty levels. The performance of the Production Agent does not change with the uncertainty in the decentralized planning, since the orders are agreed on before the period. The performance of the Production Agent with the Naïve approach has a very small variation.

Figure 17 - Attended order



Source: Author

Figure 17 presents the percentage of attended orders. The demands were settled above the supply chain's capacity in order to get a better perception of the efficiency of the resources' usage. The whole demand was, indeed, mathematically impossible to attend. As it is possible to see, the Naïve approach has a better performance in relation to the number of attended orders. This occurs because the decentralized model focuses on profits, sometimes favoring the delivery of fewer parts that provide a bigger financial return.

4.5. CONCLUSIONS

In this chapter, a procedure to apply a decentralized planning model in a specific collaborative spare parts supply chain was proposed, leading to better solutions in terms of overall costs for the given agents. Thus, the outcome model was applied and used as input data in a simulation model in order to prove its feasibility and performance compared to classical managerial approaches. The model proved to be feasible since its objective function was similar to the outcome of the simulation, and it proved to be more efficient than the Naïve approach. The framework used to find existing models and adapt them to the given supply chain coordination problem was proven to be effective, supporting the application of this collaborative approach in other scenarios.

The results of this study should be interpreted in light of a few limitations, such as the selection of a specific supply chain, which makes the generalization to other supply chains difficult. However, this limitation is offset by the quality of information obtained from a more in-depth study and by the analysis of a particularly innovative setting. In addition, more data on the probability distribution of the intelligent maintenance system forecast would also help to generate more realistic results. In order to extend the present work, different classical approaches should be added to the benchmarking phase, as well as different scenarios on the simulation.

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CONCLUSIONS

The objective of the present work was to propose a structured procedure to base an efficient application of collaborative decentralized supply chain planning in a spare parts supply chain integrated to intelligent maintenance systems.

To achieve the mentioned objective, a bibliometric analysis and an in-depth analysis were performed to identify the main research opportunities and tendencies and the main approaches in the research area. This step revealed some interesting points. First, the area is significantly well developed in terms of the proposed planning models, but it lacks validation of test cases in real scenarios with real data. Second, when it comes to linear or non-linear problem modeling, few authors scientifically base their solving method choices. Also, when it comes to collaborative planning, the decentralized planning approach is defined as more applicable in real cases, since it preserves an organization's privacy in terms of information sharing.

With such information, the third chapter of the present work shows that, when it comes to decentralized planning, most of the models are developed through Linear Programming. A characterization of the possible solving methods for Linear Programming was performed through a review of the literature, and a table was proposed to support decisions. From the table, it was possible to conclude that there are few technical indications on each solving method in today's databases, making the choice of the method be based on subjective characteristics.

Chapter four uses information from the previous chapters to endorse the application of collaborative decentralized planning in a spare parts supply chain integrated with intelligent maintenance systems. A structured procedure for applying collaborative decentralized planning was proposed and tested. The procedure proved to be effective, the approach was evidenced to be more efficient than classical managerial approaches, and the choice of the solving method was proved satisfying.

The results of this study should be interpreted in light of a few limitations. In step one, the analysis of literature data was based only on the works provided by three databases and included English-written documents only. In addition, the network provided by the software pinpoints only 7 out of 55 papers as significantly representative in the area. This number may be too modest to represent the area. Step two only considers the most classical methods, and the characteristics taken into account were also subjective in a certain way. In step three, the test case selects one specific supply chain, which makes the generalization to other supply chains difficult. However, this limitation is also offset by the quality of information obtained from a more in-depth study and by the analysis of a particularly innovative setting. Moreover, more data on the probability distribution of the intelligent maintenance system forecast would help to generate and analyze more realistic results.

As future research opportunities, a more extended search and an in-depth analysis on collaboration and supply chain planning can be performed. In addition, more approaches can be considered on the decision of solving methods, and quantitative information on the methods' efficiency can be generated by benchmark testing. In addition to these points, more classical approaches can be considered in the comparison of the output model with the structured procedure.

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APPENDIX A

Mathematical code from CPLEX

Distribution Agent:

```
//  parameters

      int k=...; // number of products
      int m=...; // number of markets
      int t=...; // planning horizon
      int f=...; // number of production facilities

      int d=...; // number of distribution center
      int n=...; // sum of all facilities
      int p=f+d; // sum of origins
      int q=d+m; // sum of destinatios

      range K=1..k;  //  set of products
      range Mq=3..m+2; // markets dest
      range T=1..t; // set of time periods
      range Tm=1..t+1;
      range F=1..f;  //  set of production
facilities
      range Dp=2..d+1;  //  set of distribution
centers or
      range Dq=1..d;   // DC dest
      range P=1..p; // set of origins
      range Q=1..q; // set o destinatinos

      int d1[1..t, 1..m*k]=...;
      int Dkmt[a in 1..k, b in 1..m, c in
1..t]=d1[c,a+k*(b-1)]; // demanded product k market
m period t

      int t1[1..q,1..p*k]=...;
      int Tkijt[a in 1..k, c in 1..q, b in 1..p] =
t1[c,a+k*(b-1)]; // cost of transporting one unit

      int Hft[F]=...;  // inventory capacity prod
facility f period t
```

```
      int Hdt[Dq]=...;  //  inventory capacity DC d
period t
      int Cft[F]=...;  // prod capacity in prod
facility f period t
      int ckf[K]=...;  // prod cap req to prod one
prod k in facility f
      int vk[K]=...;  // storage space required for
one prod k
      float pkmt[K]=...; //  market price prod k
      float wkft[K]=...; //  wholesale price
      float rkft[K]=...; //  unit production cost

      float hkft[K]=...; //  unit inventory
carrying cost prod facility
      float hkdt[K]=...; //  unit inventory
carrying cost distribution center
      int ccft[T]=...;

// variables
      dvar int+ ykijt[K][Q][P][T]; // transp quant
      dvar int+ ikdt[K][Dq][Tm]; // ending invent
in dc

      maximize sum(a in K, b in T, c in
Mq)(pkmt[a]*sum(j in Dp)ykijt[a][c][j][b])
             - (sum(a in K, b in T)(sum(c in P, j
in Q)(Tkijt[a][j][c]*ykijt[a][j][c][b]))
             + sum(a in K, b in T, c in
Dq)(hkdt[a]*ikdt[a][c][b])
            + sum(a in K, b in T, c in
F)(wkft[a]*sum(j in Dq)ykijt[a][j][c][b]));


      subject to {
            forall(a in K, b in Dq)
                  EstoquesIniciaisDC:
                  ikdt[a][b][1]==0;

            forall(a in K, b in Dq)
                  EstoquesFinaisDC:
                  ikdt[a][b][11]==0;

            forall(a in K, c in T, w in Dq)
```

```
                  DC_Inv_Balance:
                  ikdt[a][w][c] + sum(j in
F)ykijt[a][w][j][c] - sum(h in
Mq)ykijt[a][h][w+1][c] == ikdt[a][w][c+1];

            forall(a in K, b in Mq, c in T)
                  Demand_Limit:
                  sum(j in Dp)ykijt[a][b][j][c] <=
Dkmt[a][b-2][c];

            forall(a in Dq, b in T)
                  DC_Inv_Capacity:
                  sum(c in K)vk[a]*ikdt[c][a][b] <=
Hdt[a];

            forall(a in F, b in T)
                  AggProd_Capacity:
                  sum(c in K,w in
Dq)ykijt[c][w][a][b]<=ccft[b];
}


int OrdemDC1[b in T, a in K] = ykijt[a][1][1][b];
int OrdemDC2[b in T, a in K] = ykijt[a][2][1][b];

int DC1M1[b in T, a in K] = ykijt[a][3][2][b];
int DC1M2[b in T, a in K] = ykijt[a][4][2][b];
int DC1M3[b in T, a in K] = ykijt[a][5][2][b];
int DC1M4[b in T, a in K] = ykijt[a][6][2][b];

int DC2M1[b in T, a in K] = ykijt[a][3][3][b];
int DC2M2[b in T, a in K] = ykijt[a][4][3][b];
int DC2M3[b in T, a in K] = ykijt[a][5][3][b];
int DC2M4[b in T, a in K] = ykijt[a][6][3][b];


int InvDC1[b in T, a in K] = ikdt[a][1][b];
int InvDC2[b in T, a in K] = ikdt[a][2][b];
```

Production Agent:

```
//  parameters

      int k=...; // number of products
      int m=...; // number of markets
      int t=...; // planning horizon
      int f=...; // number of production facilities

      int d=...; // number of distribution center
      int n=...; // sum of all facilities

      range K=1..k;  //  set of products

      range T=1..t; // set of time periods
      range Tm=1..t+1;
      range F=1..f;  //  set of production
facilities



      int Hft[F]=...;  // inventory capacity prod
facility f period t
      int Cft[F]=...;  // prod capacity in prod
facility f period t
      int ckf[K]=...;  // prod cap req to prod one
prod k in facility f
      int vk[K]=...;  // storage space required for
one prod k
      float pkmt[K]=...; //  market price prod k
      float wkft[K]=...; //  wholesale price
      float rkft[K]=...; //  unit production cost

      float hkft[K]=...; //  unit inventory
carrying cost prod facility
      int ordDC1[T][K]=...;
      int ordDC2[T][K]=...;
      int okft[a in K, b in T] = ordDC1[b][a] +
ordDC2[b][a];
```

```
// variables
      dvar int+ xkft[K][T]; // quant prod k in F in
period t
      dvar int+ ikft[K][Tm]; // ending invent in F
      dvar int+ bkft[K][T]; // supply shortage


      maximize (sum(a in K, b in F, c in
T)wkft[a]*(okft[a][c]-bkft[a][c]))
            - (sum(a in K, b in F, c in
T)((rkft[a]*xkft[a][c]) + (hkft[a]*ikft[a][c])));


      subject to {
            forall(a in K)
                  EstoqueInicialF:
                  ikft[a][1]==0;

            forall(a in K)
                  EstoqueFinalF:
                  ikft[a][11]==0;

            forall(a in K, b in F, c in T)
                  F_Inv_Balance:
                  ikft[a][c] + xkft[a][c] -
okft[a][c] + bkft[a][c] == ikft[a][c+1];

            forall(b in T, a in F)
                  F_Inv_Capacity:
                  sum(c in K)vk[c]*ikft[c][b] <=
Hft[a];

            forall(a in F, b in T)
                  Prod_Capacity:
                  sum(c in K)ckf[c]*xkft[c][b] <=
Cft[a];
       }


       int production[a in T, b in K] = xkft[b][a];
       int inv[a in T, b in K] = ikft[b][a];
```

```
       int ccft[b in T] =
(okft[1][b]+okft[2][b]+okft[3][b]) -
(bkft[1][b]+bkft[2][b]+bkft[3][b]);
```