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Business Model Development and Operational Planning in Dynamic Manufacturing Networks

by

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To my mom and dad "Dursade ve Muzaffer Sadıç'a",
for all they have done for me.
To my 16 year old self "Şenay'a",
for always believing in my potential.

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Abstract

This thesis explores the Dynamic Manufacturing Network (DMN) business model to support collaboration between Small and Medium Enterprises (SMEs) operating in Discrete Complex Manufacturing Industries (DCMI). These industries require higher levels of functional integration due to their nature and to the complexity of their processes. Moreover, advanced optimization models are, in general, required to assist planning activities and operations management.

A Dynamic Manufacturing Network (DMN) is an opportunistic network of autonomous companies, supported by real time information sharing, and by automated business processes and functions. The DMN business model is taken as a reference through the dissertation, and its applicability is explored for SMEs collaboration in DCMI. Probably due to the novelty of the DMN business model, there is a clear lack in the literature of tools, methodologies or approaches to support this model through its life cycle.

In a first phase of the research, the DMN concept is explored in detail, and a broad but functional business model is derived. The second phase of the dissertation covers the design and development of ICT tools to support the business model at a tactical level. These ICT tools include a conceptual framework, a functional flow chart, a process flow chart, and an informational flow chart. Finally, we present a set of innovative contributions for the business model at an operational level, by developing optimization approaches to support DMN formation and operational planning. The models and decision support tools developed in this work are applied and assessed in illustrative cases, to show their adequacy and potential for real complex situations.

Resumo

Esta tese explora o modelo de negócio das Redes Dinâmicas de Produção (RDP), de forma a apoiar a colaboração entre Pequenas e Médias Empresas (PMEs), operando em Indústrias Complexas de Produção Discreta (IPCD). Devido à sua natureza e à complexidade dos seus processos, estas indústrias requerem, em geral, um elevado nível de integração funcional. Além disso, são necessários, em geral, modelos avançados de otimização para auxiliar as atividades de planeamento e a gestão de operações.

Uma Rede Dinâmica de Produção (RDP) é uma rede oportunista de empresas autónomas, baseada na partilha de informação em tempo real, e em funções e processos de negócios automatizados. O modelo de negócio de RDPs é tomado como referência ao longo da dissertação, e a sua aplicabilidade é explorada para a colaboração de PMEs em Indústrias Complexas de Produção Discreta. Talvez por ser um modelo de negócios recente, não se encontram na literatura muitas referências a ferramentas, metodologias ou abordagens para apoiar as RDPs, ao longo do seu ciclo de vida.

Numa primeira fase da investigação, o conceito de RDP é explorado em detalhe, conduzindo à formulação de um modelo de negócio abrangente mas funcional. A segunda fase da dissertação cobre o desenho e desenvolvimento de ferramentas TIC para apoiar o modelo de negócio ao nível tático. Estas ferramentas incluem uma "estrutura conceptual", um fluxograma funcional, um fluxograma de processos e um fluxograma informacional. Finalmente, apresentam-se contribuições inovadoras ao nível operacional, desenvolvendo-se abordagens de otimização para apoiar a formação e o planeamento operacional de RDPs. Os modelos e as ferramentas de apoio à decisão desenvolvidas neste trabalho são depois aplicados e testados em casos ilustrativos, para mostrar a sua adequação e potencial em situações reais complexas.

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CHAPTER 1: INTRODUCTION

This section presents an introduction to the thesis, explaining the context, listing the research objectives, presenting the adopted research methodology and providing a dissertation outline.

1.1. CONTEXT

Within current global markets, there is fiercer competition between networks than between companies (Viswanadham and Gaonkar, 2003; Camarinha-Matos *et al.*, 2009). In the earlier stages of networked manufacturing, companies were relying on forming long-time partnerships via vertical integration. However market turbulence and globalization challenged them to look for more flexible integration solutions. With the support of ICT tools, companies now have the opportunity to virtually integrate, cooperate and collaborate with partners from remote regions of the world.

Supply chain collaboration has recently been widely referred and utilized as a business strategy. Large corporations such as HP, Amazon, Wall Mart, Procter and Gamble, Henkel and Dell Computer, etc. have implemented very successful collaboration practices (Danese, 2011; Kristianto, Ajmal and Helo, 2011). Supply chain collaboration can be defined as a joint process of autonomous companies in which they share risks, responsibilities and benefits (Simatupang and Sridharan, 2005a). Among the proved benefits of supply chain collaboration the following points can be listed: higher profit margins and market share, better customer service, increased bargaining power and innovation potential, etc. (Simatupang and Sridharan, 2002; Viswanadham and Gaonkar, 2003).

For Small and Medium Enterprises (SMEs), collaboration is not only a means of performance boost, but also a tool for survival (Camarinha-Matos, 2009). After the recent economic crisis led many SMEs to bankruptcy, the European Union has given great importance to SME sustainability. SMEs constitute a very important part of employment rates and GDP in EU. According to the Eurostat statistics, in 2012, the number of micro, medium and small-sized enterprises in EU-27 adds up to more than 20 million. These enterprises employ more than 86 million people which stand for 66.5 % of all EU employment. During 2012, SMEs as a whole had a contribution of 57.6 % to the whole gross value added generated by the private, non-financial economy in Europe (*Annual Report on European SMEs*, 2013). Individually SMEs are dependent on Original Equipment Manufacturer (OEM), and lack competency in product development and technology.

However, through collaboration, it is possible for them to benefit from collective economies of scale, and from their individual flexibilities in internal operations.

Among the recently developed collaborative Business Models, one can list Virtual Enterprises (VE), Strategic Partnerships, Global Manufacturing Networks, Dispersed Manufacturing Networks, Agile Manufacturing Networks, Build-to-order Supply Chains and Dynamic Manufacturing Networks (DMN). Within these emerging business models Dynamic Manufacturing Networks (DMN) come out as opportunistic networks of autonomous companies, supported by real time information sharing and automated business processes and functions (Viswanadham and Gaonkar, 2003; Markaki, Kokkinakos, *et al.*, 2013). Since the DMN business model was recently introduced, the related literature lacks tools, methodologies or approaches to support it through its life cycle. The overall DMN Management process requires sophisticated ICT tools that are composed of integrated models of several submodules.

In this thesis, we aim to focus on the application of the Dynamic Manufacturing Network (DMN) Business Model to SMEs functioning in Discrete Complex Manufacturing Industries. These industries require a level of integration higher than other industries, due to the complexity of their processes (Supply Chain Digest, 2004). Moreover, for the same reason, they also need proper optimization based models that can assist their operational planning. Through the thesis, we will explain the DMN business model explicitly and will derive a proper and functional business model from a rough initial concept. Once the business model is clearly defined, our objective will be to create decision support tools and models to assist DMNs through their operational planning. Illustrations of decision support tools are presented, in order to show the adequacy of the developed models. It should be noted that during the thesis, our objective is not to investigate the performance of the decision support tools, but to prove the adequacy of the models and illustrate their applications.

1.2. Objectives of the Thesis

In this thesis, we aim to develop a suitable business model to support SME Collaboration in Discrete Complex Manufacturing Industries, to design the necessary ICT functionalities to assist its main processes and to design decision support tools to support operational planning. Through the thesis, the Dynamic Manufacturing Network business model is investigated for further application on Discrete Complex Manufacturing Industries. Moreover, we have applied and assessed the decision support tools on illustrative examples inspired by real situations

Even though collaboration is inevitable for performance boost, planning in collaborative environments is often very complicated. Collaborative planning is specifically challenging in collaborative networks of discrete complex products manufacturing companies, where products go through a high number of manufacturing processes, and require an effective planning to be done. The need for customized production and the increasing market turbulence are other main challenges faced by discrete complex manufacturing industries. These industries need new collaboration forms to build trust between partners, to assist their business processes, to plan their operations, and to deal with numerous perturbations that can occur during the operational cycle.

DMN is a collaboration form that can answer the mentioned needs. While other collaboration forms, such as the Virtual Enterprise or the Extended Enterprise, function with cooperation based on limited information sharing, the DMN business model both fulfills the requirements of collaboration and cooperation. In the DMN business model, a collaboration base is settled through an automated ICT platform and trust is provided through the network via agreements and control mechanisms. These preconditions enable the rapid formation and optimized planning of DMNs.

In this study, different protocols and decision support systems to assist the coordination of Dynamic Manufacturing Networks are going to be designed, and new methods for coordination are going to be explored. The output of the study is a set of designed “decision support tools” based on optimization models that will specifically address the operational planning of DMNs. These tools will provide a functional business model to support SME collaboration and allow the decision maker to explore different perspectives on the solutions of DMN formation and on the operational planning problem.

The main research questions to be answered by this doctoral project are the following:

- How can the DMN business model concept be implemented for collaboration of SMEs in discrete manufacturing industries?
- How can we align the long-term strategy of the business model with the ICT requirements?
- How can we link different functions via a “business framework” in order to support the business model?
- Which different objectives should be considered in DMN operational planning?
- How can we create optimization based models to support DMN formation and operational planning?

1.3. METHODOLOGY

In this thesis, we have followed a three step methodology that covers consecutive planning levels. These three levels can be designated as: Strategic Level, Tactical Level, and Operational Level.

Strategic level decisions cover long-term issues such as the business model, decision making alignment, supply chain integration, information sharing, organizational layers, etc. Once the strategic level parameters and characteristics are selected and settled, a tactical level planning will be built over them. At this level, medium-term decisions, such as the configuration of ICT tools and the design of business model functions to support the strategic level decision, will be taken. Since DMNs are highly dependent on ICT tools, this stage requires a consistent effort that includes a strategy to action translation and alignment. Moreover, the information flow between different business functions should be decided in order to express the overall functioning of the business model. Finally, the operational level decisions include the development of models and decision support tools to assist different DMN life cycle phases. It is also important for operational level decision making tools to be in alignment with tactical and strategic level objectives.

Figure 1 presents the methodology with the different stages of research, and the identification of the utilized tools. During the first stage of the research, which was presented in Chapter 2, we have performed a theoretical, qualitative study that is built upon a comprehensive literature review on collaboration, collaborative business models and Dynamic Manufacturing Networks. Initially we have defined a set of research questions that guided us in the development of a business model capable of supporting SMEs in Discrete Complex Manufacturing Industries. In this exploratory section of the thesis, the main characteristics of this type of industries and the challenges that are faced by SMEs were investigated. Then, a descriptive research on "Dynamic Manufacturing Networks" and "Collaborative Networks" was done. To conclude this part of the dissertation, we have conducted an explanatory research where different DMN types were defined, a suitable business model was selected, and a business framework was developed.

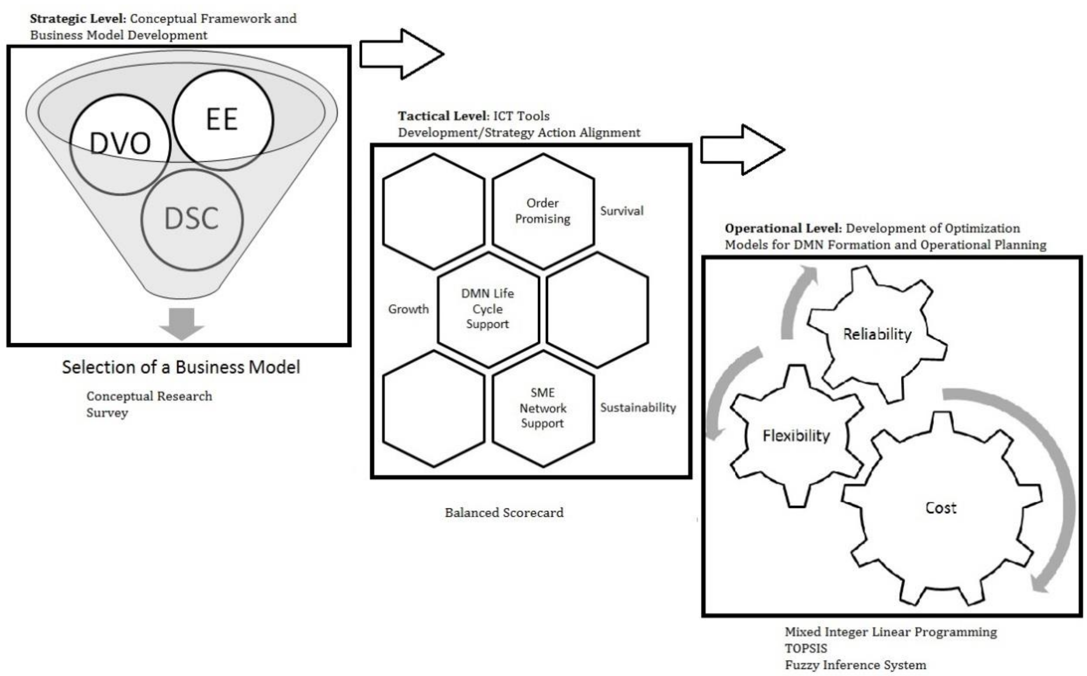

Figure 1 Methodology

The second stage of the research, which was presented in Chapter 3, consists of a theoretical qualitative study that aims to support the development of ICT tools for the new business model. Initially the business context is explained and research objectives are listed. In this section the research framework of Chapter 3 is proposed and the methodology is presented. The second section of Chapter 3 covers an explanatory research that aims to develop an SME network strategy, and to translate its components, to ICT requirements, in order to align the business model strategy with ICT tools. In this strategy translation and ICT alignment, a Balanced Scorecard approach was adopted. The Balanced Scorecard is a strategic planning and management tool that is extensively used in government, business environments and industry. The Balanced Scorecard approach was chosen due to its structure that explicitly supports financial and non-financial aspects of organizational performance, and its capability to translate strategy to action. After the scorecard implementation, we present a literature review that explores ICT tools to support Strategic and Operational Networks. Finally, we present several ICT tools to support an adequate functioning of the business model.

In the third phase of the research, which covers the operational level decision making, we present three distinctive quantitative studies with different objective functions for the DMN formation process. Chapter 4 and Chapter 5 and Chapter 6 all contribute to the planning function in the operational level of the business model. Our objectives in these chapters are to develop models that approach the DMN formation and operational planning problem from different perspectives, and to try different solutions, in order to provide the decision maker a set of alternative solutions.

DMN operational processes are exposed to many risks and therefore need proper methodologies to minimize disruptions. During the study, apart from cost minimization, we have also considered disruption minimization as a part of our operational planning objectives. While Chapter 4 focuses on the maximization of reliabilities of the manufacturing partners, Chapter 5 deals with the maximization of operational flexibility. On the other hand, Chapter 6 combines the perspectives developed in Chapter 4 and Chapter 5 in one single model.

While maximizing reliability minimizes the risk of possible future manufacturing disruptions, maximizing operational flexibility increases the possibility of adaptation in case of a possible future disruption. Our objectives in Chapter 4 and Chapter 5 are to explore these two different perspectives and to illustrate the proposed approaches. The decision maker is guided to extract results of these approaches, and to choose a proper operational plan and discuss its implications.

As the first component of the operational planning decision support tools, Chapter 4 integrates order, manufacturer and customer characteristics into the DMN planning. Initially, a literature review on operational planning in networked manufacturing is presented. The next section covers the methodology followed through the study. As part of the methodology, initially the TOPSIS multi-criteria decision making approach was utilized to calculate Order Criticality, Customer Priority and Manufacturer Reliability indices, through customer, order and manufacturer data. TOPSIS was selected because of its mathematically sound basis and easy application. Then, a fuzzy inference system was developed to translate Order Criticality and Customer Priority indices into an Order Priority index. Fuzzy inference is generally utilized when it is not possible to explicitly relate model parameters with the output. In this part of the study expert opinions were collected and translated into rules that relate input values with output values. Finally a multi objective Mixed Integer Linear Programming (MILP) model was developed. This model has two objective functions: cost minimization and reliability maximization. An Order Criticality index and a Manufacturer Reliability index were used as inputs to the multi objective model "Reliability" objective function. The other selected objective was cost minimization. A MILP approach was selected for the problems, since they are easily formulated via standard techniques and efficiently solved with commercial solvers, when applied to small and medium sized instances. The methodology is demonstrated with reality inspired data through an illustrative example. Finally a Decision Support System that allows decision makers to reach alternative network configurations for varying alternative weights is designed.

Another DMN formation and operational planning model was developed and is presented in Chapter 5. This model aims to generate flexibility based operational plans for DMNs. In the initial exploratory part of the study, the research context is introduced and two literature reviews on "Planning in Short Term Supply Chains" and "Flexibility concerns in DMN Planning" are presented. Then a mathematical methodology is developed by utilizing MILP formulations and a weighted sum multi objective optimization technique. Two main objectives are defined as cost minimization and flexibility maximization. In order to mathematically represent flexibility, two measures on "Slack Capacity" and "Slack Time" were developed and embedded into the model. Finally solutions are depicted via an illustrative example, and several scenarios were analyzed in order to understand how the model reacts to different types of data.

Finally in Chapter 6, we join the two perspectives on operational planning, in a single model. While in Chapter 4 we have focused on developing reliable plans and in Chapter 5 on developing flexible models, Chapter 6 aims to generate both reliable and flexible plans. By changing the weights of reliability, flexibility and cost in the multi objective MILP model, different interesting outcomes are obtained. Finally we propose three network configurations with different parameters.

The main intended thesis outcomes are:

- a DMN inspired business model that fulfills the needs of SMEs in discrete complex manufacturing industries;
- a business model framework that covers different functions of the business model;
- optimization models to support the DMN business model in the operational level, integrating different objectives that are related to DMN formation and operational planning decisions along with cost concerns.

1.4. Outline of the Dissertation

In Chapter 1, we present an introduction to the thesis. This chapter aims to introduce the reader to the context, present guidance about the research, and depict the overall structure of the thesis. Initially, in Section 1 and Section 2 of Chapter 1, the context of the research is explained and research objectives are listed. Then, through Section 3 and Section 4 the methodology is presented, and an outline to the dissertation is provided.

Chapter 2 covers a qualitative study where a new business model is developed for SMEs in discrete complex manufacturing industries. In Section 2, the research context is explained through a set of research questions and the adopted methodology. Section 3 covers the research background. The research background is composed of explanations of discrete complex manufacturing industry characteristics and the main challenges faced by SMEs, feeding the presentation of business model requirements. Later, in Section 4 an in-depth investigation of the DMN business model is provided. This section covers the definition and the characteristics of DMNs, and an explanation of the business model, benefits and risks of the DMN business model, DMN ownership and prerequisites and DMN life cycle. In Section 5, collaboration, collaborative networks and collaborative networks taxonomy are explored, in order to understand where DMN as a Virtual Enterprise (VE) fits within the taxonomy. As a part of the same section, the developed taxonomy of DMNs is presented. The DMN taxonomy was inspired by the CN taxonomy. Through Section 6, the developed business model was introduced and organizational layers were presented. The chapter is followed by showing research gaps and opportunities in Section 7. Section 8 presents the conclusions of the study. In Chapter 2, the research was conducted for the strategic level of the business model.

Chapter 3 includes the development of a conceptual framework and a functional, a process and an informational flow, to support the developed business model. In Section 2, the research background and objectives are explained through the presentation of the business context and the identification of research objectives and methodology. During Section 3, an SME network vision is proposed with three main dimensions: sustainability, growth and survival. Later, a Balanced Scorecard approach is implemented, in order to translate the SME network strategy to an operational level Information Technology requirement list. These requirements guided the development of ICT tools. The components of Balanced Scorecard are presented as a Sustainability Balanced Scorecard, a Growth Balanced Scorecard and a Survival Balanced Scorecard. Section 4 covers two literature reviews on “Tools to Support Management and Planning of Strategic Networks” and “Business Frameworks and Processes to support Operational Networks”. Then, in Section 5, ICT tools are developed for the business model based on the literature and the IT initiatives derived from the strategic planning through the implementation of the Balanced Scorecard. A conceptual framework and a functional, a process and an informational flow are presented as parts of the ICT tools. The Chapter is concluded in Section 6.

Chapter 4 presents a multi objective Mixed Integer Linear Programming (MILP) model that integrates order, customer and manufacturer characteristics into DMN formation and operational planning. This chapter follows a three stage methodology that is composed of TOPSIS, a fuzzy inference system and a multi-objective MILP model. In Section 2, a literature review on Operational Planning in Networked Manufacturing is conducted. In Section 3, the methodology is presented explicitly by demonstrating all modeling stages. In Section 4, the developed methodology is applied on an illustrative example and the results are revealed. Finally Section 5 introduces a decision support system which allows decision makers to reach alternative network configurations for different alternative weights.

In Chapter 5, a multi-objective MILP model that integrates reactive flexibility measures for operational planning is presented. In Section 2, the context is explained and two literature reviews on "Planning in Short Term Supply Chains" and "Flexibility Concerns in DMN Planning" are presented. Then in Section 3 the methodology is presented, based on a MILP model and a set of flexibility measures. Later in Section 4, an illustrative example and the results are presented. In Section 5, the effects of demand and fixed partner selection cost parameters on the results are explored via scenario analysis.

Chapter 6 covers the development of potential DMN configurations and plans for a multi objective model that is composed by reliability, flexibility and cost objective functions. Integrating the objective functions of both Chapter 4 and Chapter 5 enables the creation of Dynamic Manufacturing Networks that both minimize the risk of disruption and maximize the capability to react to disruptions. By giving different weights to the three objective functions, we have explored optimal costs, optimal reliability and optimal flexibility values. Finally we have proposed three network structures that are reliable, flexible and with reasonable costs.

Chapter 7 is the final chapter of the thesis. Section 1 covers the main contributions of our work and Section 2 presents the limitations of the study and provides a list of required possible future works.

Chapter 2: A Business Model to Support SME Collaboration in Discrete, Complex Manufacturing Industries

In this chapter, our primary objectives are to understand the challenges and needs of Small and Medium Enterprises (SMEs) operating in discrete, complex manufacturing industries (DCMI), to understand the so-called Dynamic Manufacturing Network (DMN) business model, to assess the applicability of this model to the context, and to propose a new collaboration-based business model.

After providing a brief introduction to the study in Section 1, we present the research context in Section 2, defining the methodology adopted for the research and listing a set of research questions. Section 3 covers DCMI characteristics and the current challenges faced by SMEs. This investigation led us to build our perspective on the essentials of a new business model. Section 4 presents the DMN business model, in order to understand its characteristics. DMN business model is explored in detail since it is considered as the potential business model for application. Section 5 consists of a literature review on collaboration and Collaborative Networks (CN). Moreover, a classification of DMNs is also provided which was inspired by business models within the CN taxonomy. In Section 6, a suitable business model for the context is selected within the classified DMN types and its organizational layers are developed and explained. This section also presents a list of identified functionalities and business processes required for the developed business model. In Section 7, further research gaps and opportunities are listed. Finally we conclude the study in Section 8 with a summary of the main findings.

2.1. INTRODUCTION

Collaborative business models such as the Virtual Enterprise (VE), the Virtual Organization (VO) or the Virtual Organization Breeding Environment (VBE) have been more and more commonly implemented in practice. The Dynamic Manufacturing Network (DMN) is referred as one these emerging business models, as opportunistic networks of autonomous companies, supported by real time information sharing and automated business processes and functions (Viswanadham and Gaonkar, 2003; Markaki, Kokkinakos, *et al.*, 2013). DMN is a recent business paradigm that was developed as an extension of the VE concept, by applying it to the manufacturing industry (Papakostas *et al.*, 2014).

In this study, we aim to review the current literature on DMNs and come up with a business model that fulfills the requirements of both discrete, complex manufacturing industries (DCMI) and SMEs. These industries are built upon very complex production processes making their planning more complex than it is in other manufacturing industries. In order to deal with such challenges, more integrated collaborative business forms need to be developed. The DMN business model with its automated processes and long term identity emerges as a potential tool that can satisfy these requirements.

Since DMN is a newly emerging business model, the concept is not yet very clear, thus needing to be further developed in order to be applicable to specific industries. While the literature generally describes the DMN business model and conceptualizes it to be applicable to business environments, in this study we specifically focus on SME collaboration in discrete, complex manufacturing industries.

Initially, we have found out business model requirements by investigating industry characteristics and SME challenges. Then the DMN business model and its characteristics were explored in detail. Literature on DMN management and operational planning is currently limited and the related terminology is not very well established. In order to better understand issues associated to the formation and the operation of DMNs, we have also looked for insights from connected research areas, namely Supply Chain Collaboration and Collaborative Networks (CN). By combining our findings with a critical perspective, a

DMN taxonomy was developed. In the next stage of the study, a business model was selected among the DMN taxonomy by comparing business model capabilities to requirements. Then, the organizational layers of the developed business model are explained in detail. The lifecycle of the business model is explored and business model functionalities are presented. Finally research gaps and opportunities on the new business model are presented.

The following Section covers the adopted methodology and the developed research questions, as considered through this Research Project.

2.2. RESEARCH CONTEXT

In order to provide a structure to approach this multi-dimensional research problem, we have come up with the research questions below. After the research questions are presented, the methodology adopted for this study will be explained.

2.2.1. BUSINESS MODEL DEVELOPMENT RESEARCH QUESTIONS

The following research questions have been identified for Chapter 2:

- What are the requirements of a collaborative business model to support SMEs in discrete complex manufacturing industries?
    - What are the characteristics of discrete complex manufacturing industries?
    - What are the challenges faced by SMEs in this context?
- What are the main characteristics of the DMN business model?
    - How does DMN function?
    - What are the strengths and weaknesses of the DMN business model?
- What is collaboration and how can the DMN business model be classified within the Collaborative Networks taxonomy?
    - What are the different types of integration?

- How can we classify different types of CNs?
- How can we classify different types of DMNs?

- What characteristics must a business model have to satisfy practical requirements?
  - Which DMN type fulfills the identified business model requirements?
  - What are the organizational and planning layers of the business model?
  - What are the functions of the DMN business model?
- Which research gaps and opportunities can be drawn from the proposed business model?

2.2.2. Methodology

In order to guide this qualitative, literature review-based, conceptual research, we have defined the research stages presented in Figure 2. Following the research steps identified in each stage, will lead us to fulfill the main objective of the study: the development of a business model to support SME collaboration in discrete complex manufacturing industries (DCMI), by taking the DMN business model as the primary research reference.

The study starts with the exploration of business model characteristics for SMEs in DCMIs. Then we turn our focus into the main DMN business model characteristics. In Step 3, the collaboration concept and Collaborative Network taxonomy will be investigated. Our main objective in this step is to derive knowledge from the literature on Collaborative Networks to the DMN context. In the next step, inspired by the CN taxonomy and the DMN Characteristics, a new DMN classification will be proposed. This will provide us with a list of possible business models that can be selected for the identified framework. In Step 5, a business model will be selected among the DMN types, by comparing their capabilities with business requirements.

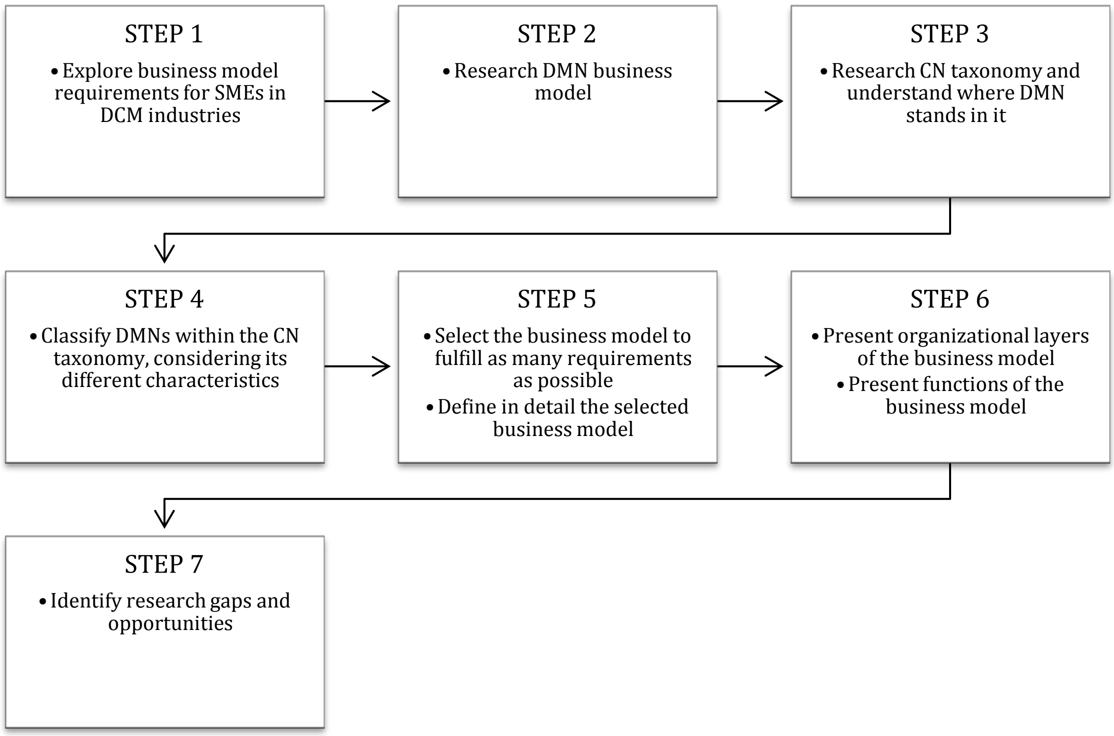

Figure 2 Research methodology

The next stage focuses on the selected business model and presents organizational layers and functions of that business model. As the last step, research gaps and opportunities will be highlighted. These research gaps are important in order to direct the rest of the research pursued in this dissertation.

2.3. RESEARCH BACKGROUND

In order to support SMEs either individually or collectively, it is important to initially understand their shortcomings and opportunities for growth. In this section, we have summarized the characteristics and the needs of Discrete Complex Manufacturing Industries, and some common internal and external challenges faced by manufacturing SMEs in the current economy.

2.3.1. DISCRETE COMPLEX MANUFACTURING INDUSTRY (DCMI) CHARACTERISTICS

Discrete Complex Manufacturing Industries (DCMIs) is the generic name for high tech industries such as semiconductor, automotive, electronics, defense or telecommunication industries (Viswanadham and Gaonkar, 2003; Pan and Nagi, 2010). Common characteristics of these industries are the following (Supply Chain Digest, 2004):

- complex, multi-level bills of material;
- multiple product configuration options;
- complex product lifecycle planning and management environments;
- multi-tier and/or multiple sales channels.

Since these industries have high degree of product variety and complexity, it is not possible to predict the future demand composition by using forecasting methods. The common solution to this drawback is implementing an order-driven supply chain strategy, where production is initiated by customer orders, and the supply chain holds as minimal stock as possible. Order-driven supply chains need to quickly plan their operations and rapidly process orders, in order to minimize customer lead time. The key to speed lies in supply chain integration via Information and Communication Technologies (ICT) applications through different elements of a supply chain.

There are two main stages in implementing supply chain integration, in an order-driven network. Initially, each network partner needs to integrate their internal operational functions through an intra-organizational ICT tool, such as ERP or MRP. Then, network wide inter-organizational integration needs to be settled by connecting shop floor data to a joint supply chain framework (Pinedo, 2009). Thus, a manufacturing network operating in DCMI needs to be treated as a system, and should be supported by ICT frameworks that link, plan and orchestrate operational flows among network members (Chen and Li, 2013).

In DCMI production and logistic planning, decision makers need to be supported by models and algorithms that are fed by manufacturing and order related data. Production and transportation planning problems of order driven networks functioning in a DCMI are in general have an intrinsically hard and combinatorial nature (NP-hard). These problems can be formulated by either multi stage lot sizing and cyclic scheduling models or single/parallel machine scheduling models (Pinedo, 2009). The characteristics of planning in discrete manufacturing industries and continuous manufacturing industries are compared in Table 1, as a way to provide an understanding of the planning complexity in discrete complex manufacturing industry. (Pinedo, 2009)

Table 1 Comparison of Discrete and Continuous Manufacturing Industry (DCMI) Characteristics

Characteristics	Discrete Manufacturing Industries	Continuous Manufacturing Industries
Planning horizon	- short - it also shortens as product moves more downstream in the supply chain	- long
Schedule changes and adjustments	- frequent	- less frequent
Mass customization and product differentiation	- significant amount is required	- does not play an important role

2.3.2. Challenges of SMEs

The consequences of recent global crises revealed how relevant SMEs are in today's economy. SMEs constitute 70% of the world's manufacturing power and are taken as crucial in the globe's economic and ecologic sustainability (Ates and Bititci, 2011). Recently, many domestic and regional economies around the world have been launching programs to support SME collaboration. The 2013 EU industrial policy also highlighted SME collaboration as a tool to create an EU economy that is competitive, innovative and capable of withstanding global challenges (*Annual Report on European SMEs*, 2013).

Despite their cumulative power, individually SMEs are vulnerable to market conditions and weak in terms of performance, market share and quality. While some of these challenges arose from their small scale and today's market dynamics, there are also some problems due to the organizational and managerial structure of SMEs. Even though the rules of the globalization game are detrimental to SMEs, individually and collectively there is a lot of room for improvement.

As internationalization has given large enterprises the opportunity to reach distant markets, for SMEs it created a big challenge. Since SMEs lack a networking background, capabilities and know-how in dealing with internationalization issues, they mainly serve in domestic markets (Char, Yasoa and Hassan, 2010). Nevertheless, even the domestic markets are nowadays invaded and dominated by large scale international enterprises. As a consequence, in order to avoid competition with their large peers, SMEs either focus on safer niche markets or settle as suppliers in Original Equipment Manufacturer (OEM) driven supply chains (Noori and Lee, 2006). During the recent economic crisis, many SMEs experienced tremendous financial problems and even bankrupted when their long term customer OEMs were hit by the crisis. Even though large corporations managed to bounce back from their losses by reaching alternative markets and creating new strategies, SMEs suffered from the lack of alternative customers. During 2012, large EU enterprises announced a decline in value of €8.6 billion, medium-sized EU enterprises showed the highest loss in value amounting to €17 billion, followed by micro-enterprises (€14 billion) and small-sized enterprises (€13.2 billion) (*Annual Report on European SMEs*, 2013). To survive and compete, SMEs have to find ways to reach international markets and alternative customers.

SMEs also have some shortcomings in the way they manage their internal processes and managerial structure. Most of the manufacturing SMEs are still working with poor management skills, while large enterprises successfully utilize ICT tools and automation. If SMEs cannot meet the basic market needs such as cost, quality or on time delivery, their main competencies; specialization and flexibility cannot be considered as an added value. To survive and prosper, SMEs are challenged to improve and integrate their operations and industrialize their production processes (Svensson and Barfod, 2002). Integration should in fact extend to an inter organizational level, if they are willing to grow and reach international scale (Hemilä, 2010).

Another main shortcoming of SMEs is their short-term focus. They need to move their attention to long-term objectives and external communication, if they want to attain sustainability. SMEs need to network, collaborate and stand together against their large-scaled peers. To achieve these goals, SMEs need to go through change management processes and transform their management structures. It is important for them to consider organizational and personal dimensions in change processes, along with operational dimension (Ates and Bititci, 2011). In the long run, collaborative networks of SMEs can be a platform for R&D and innovation as well (Noori and Lee, 2006).

Collaboration in fact serves as an instrument to deal with these challenges. By forming virtually integrated global SME networks supported by ICT tools and business processes, it will be possible to solve domestic demand dependency, and increase the bargaining power of SMEs against OEMs.

2.3.3. Business Model Requirements

Table 2 presents some requirements to develop a business model to support collaboration among SMEs in discrete complex manufacturing industries. The first column on the left of Table 2 lists the challenges of DCMIs as summarized in subsection 2.3.1. The table provides some contributions to answer the first three research questions presented in Section 2.2.1

Table 2 also shows business model requirements that correspond to DCMI characteristics. As presented in Table 2 these requirements are: order-driven supply chain strategy; ICT integration; network wide supply chain frameworks; and optimization based models. These requirements may satisfy the high level integration need of this industry. On the other hand, challenges faced by SMEs are presented on the right column. The associated business model requirements are: reaching global markets, e-commerce, collaboration, process integration, sustainability research, and strategic planning. These features can basically answer internationalization, strategic planning and ICT integration needs of SMEs. Note that, there are also many SMEs that are successful in these dimensions and creating value with efficiency. However, this list indicates the shortcomings of less successful SMEs that are willing to collaborate and increase their performance. Sustainability and strategic planning requirements highlight the problems associated with short term thinking of SMEs and points out the need to address their main motivation for collaboration: survival.

Table 2 The challenges and requirements for the researched business model

Discrete Complex Manufacturing	Business Model Requirements		Small and Medium Enterprises
Challenges			Challenges
Complexity and variety in:	ORDER- DRIVEN SUPPLY CHAIN STRATEGY	Reaching global Markets / E-commerce	Domestic Market dependence
bill of materials			
product configuration		E- commerce	OEM dependency
product life cycle planning			
supply chain sales and channels		Collaboration	Poor barganing power
Need for accuracy and speed in	- ICT INTEGRATION - NETWORK-WIDE SUPPLY CHAIN FRAMEWORKS - OPTIMIZATION BASED MODELS	Process Integration	Lack of control in internal operations
real time information /data			
production planning		Sustainability Research	Short term focus
logistics planning			
detailed and synchronized operational plans		Strategic Planning	Lack of strategy

2.4. DYNAMIC MANUFACTURING NETWORK (DMN) CONTEXT

In this section, we aim to make an introduction to the DMN business model by understanding its functioning and by exploring its characteristics such as ownership structure and life cycle. In order to understand the applicability of the DMN business model to the research context, initially it is important to improve our knowledge on DMNs.

2.4.1. DEFINITION AND CHARACTERISTICS OF DMNS

A DMN is a temporary or long term collaborative manufacturing network composed of geographically dispersed SMEs and/or OEMs (Viswanadham and Gaonkar, 2003; Markaki, Kokkinakos, *et al.*, 2013). Through real time information sharing, communication and integrated processes, DMNs enable cultivation of cooperation among potential partners of the value chain (Markaki, Kokkinakos, *et al.*, 2013). While the DMN concept is first mentioned by (Viswanadham and Gaonkar, 2003) and the associated business model is researched under different names, the most complete academic research in DMNs is presented by the IMAGINE project.

The characteristics of DMNs can be summarized as follows (Markaki, Panopoulos, *et al.*, 2013) :

- DMNs are promptly formed to satisfy one time or repetitive business opportunities and will be dissolved once the order is delivered;
- DMNs are formed and operated through an IT-supported business model that is incorporated in a collaborative platform;
- Operational processes of DMNs are assisted by automated and optimized processes through their life cycle;
- DMN partners share real time or close to real time data with the collaborative platform.

As opposed to traditional supply chains, where production planning is optimized among long term members of a static network, DMNs have a dynamic structure, where a new manufacturing network is formed through members of the partner pool for each business opportunity (Markaki, Panopoulos, *et al.*, 2013). The new DMN can be formed by either reconfiguring an existing DMN or by designing a completely new DMN in accordance with order requirements (Papakostas *et al.*, 2014). Several factors can affect the DMN composition, in terms of selected partners and operational plan. (Viswanadham and Gaonkar, 2003) observed that buyer location is one of these factors since, in a dispersed manufacturing context, network configuration dynamically changes with the buyer location due to the differences in transportation and production lead times and costs. Other factors affecting DMN composition can also be referred such as labor capability differences, energy and oil prices, transportation structure, international legislations or taxation system (Zhang, Luo and Huang, 2012).

2.4.2. Business Model

The DMN business model acts as an interface between the customer side and the manufacturing side of the value chain. Unlike most of the CNs that are formed and operated directly by people, in a manual way, DMNs are assisted by an automated collaborative platform through all stages of their life cycle. Figure 3 depicts the high level structure of the DMN business model. While a collaborative platform integrates potential manufacturing partners, the e-marketplace supports customer communication and assists the order promising. Typically, the e-marketplace presents product catalogs to the customer, receives customer orders with the required information, such as bill of materials, detailed manufacturing processes, product characteristics and other order specifications, and takes this information to the Collaborative Platform. From that point on, the Collaborative Platform handles the manufacturing tasks, such as setting the DMN configuration, generating joint production plans, executing operational control and monitoring, performing risk evaluation and management, and running sharing mechanisms.

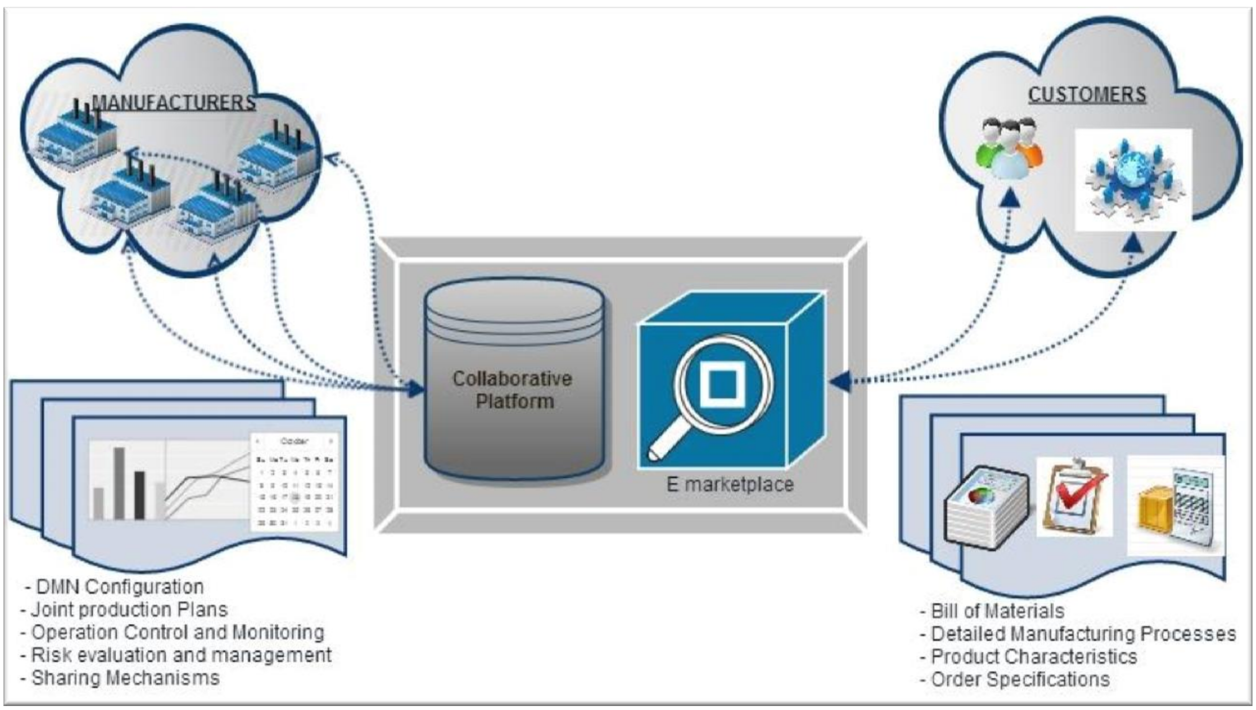

Figure 3 The DMN integrated platform

Even though the DMN business model has many potential benefits, there are some ICT and soft prerequisites that have to be set up, before initiating the business model. On the ICT requirements side, we need to build an automated collaborative platform, and to develop models, processes and algorithms to support DMN tasks. The development of the ICT platform is costly and time consuming. Among the soft prerequisites, we need to consider transparency, fairness, group cohesion, trust, openness, security and interoperability issues (Papakostas *et al.*, 2014). Only after the prerequisites of the business model are resolved and the system is settled, may the potential partners be willing to share real time information with the collaborative platform (Viswanadham and Gaonkar, 2003).

2.4.3. Benefits and Risks of the DMN Business Model

As a holistic approach to supply chain management, DMNs lead to several performance improvements of the whole network. Through optimized decision support tools and automated business processes, a DMN offers time savings in production planning and demand response, cost reduction by taking advantage of different cost structures and enhanced operations through automated, visible processes (Markaki, Kokkinakos, *et al.*, 2013).

(Markaki, Panopoulos, *et al.*, 2013) highlighted the following expected benefits of the DMN business model:

- reduction of time-to-market up to 25% ;
- reduction of lead time up to 20% ;
- improved efficiency of co-operation processes (manufacturing network design, re-configuration and re-engineering) up to 30% ;
- decrease of product cycle times up to 50% ;
- decrease of life cycle costs up to 30% ;
- decrease of maintenance costs up to 30%.

However, unlike the static supply chains that work with the same partners for a long period of time, DMNs face operational risks on a daily basis (Markaki, Panopoulos, *et al.*, 2013). DMNs are very prone to disruptions since they are formed by manufacturing partners operating from dispersed geographical locations. Moreover, the autonomous structure of partners also makes it impossible to control their internal operations and brings a behavioral risk to the network. (Markaki, Kokkinakos, *et al.*, 2013) listed the following risks of this business model:

- information security and trust: sharing detailed, real time data makes partners vulnerable, while information security should be taken as a priority,

- poor configuration, design and management of the network: DMNs rely on real time data. Thus problems in information quality may result in poor DMN configuration,
- DMN dissolution when key partner drops out of the network: if a key partner withdraws the whole network faces failure risk. Responsibilities should be legally identified during DMN formation;
- transition issues: a DMN requires a shift in each company's strategic alignment. The transition process may face resistance from some partners;
- competitive threats after a partner's withdrawal: when a member decides to withdraw from the network, issues related to intellectual property rights and know-how that was accumulated during DMN operations may arise;
- loss of partner's reputation: when a partner fails to follow the operational plan, the reputation of the whole network is jeopardized. To deal with this risk, it is important to monitor deviations from the actual plan and reschedule the operations to succeed in delivering orders in time.

2.4.4. DMN Ownership Structure and Life Cycle

DMNs are either orchestrated by a strategic alliance that is composed of partner SMEs, or by a broker or by an OEM (Markaki, Panopoulos, *et al.*, 2013). While the overall control of an SME Strategic Alliance increases the collective bargaining power of the SMEs, control of an OEM provides many operational and cost benefits over the whole value chain.

The DMN life cycle is presented in Figure 4 with three main phases: Configuration; Design and Execution; Monitoring and Management (Markaki, Panopoulos, *et al.*, 2013). The whole process starts when a customer order is received via the e-marketplace. In the DMN configuration phase, high level production plans with the associated schedules are created, and tests are performed on the initial DMN configuration. Later, in the DMN design phase, detailed schedules are developed, and production is synchronized among DMN partners by mapping process segments to shop floor operations. Throughout the DMN Execution, Monitoring and Management phase, operations are monitored through their execution and if there is a disruption, changes are made to the operations. The process stops once the DMN delivers the order to the customer and the DMN dissolves by sharing benefits. Note that, even though this reference excludes, many studies also DMN dissolution as a last phase of the VE/DMN life cycle.

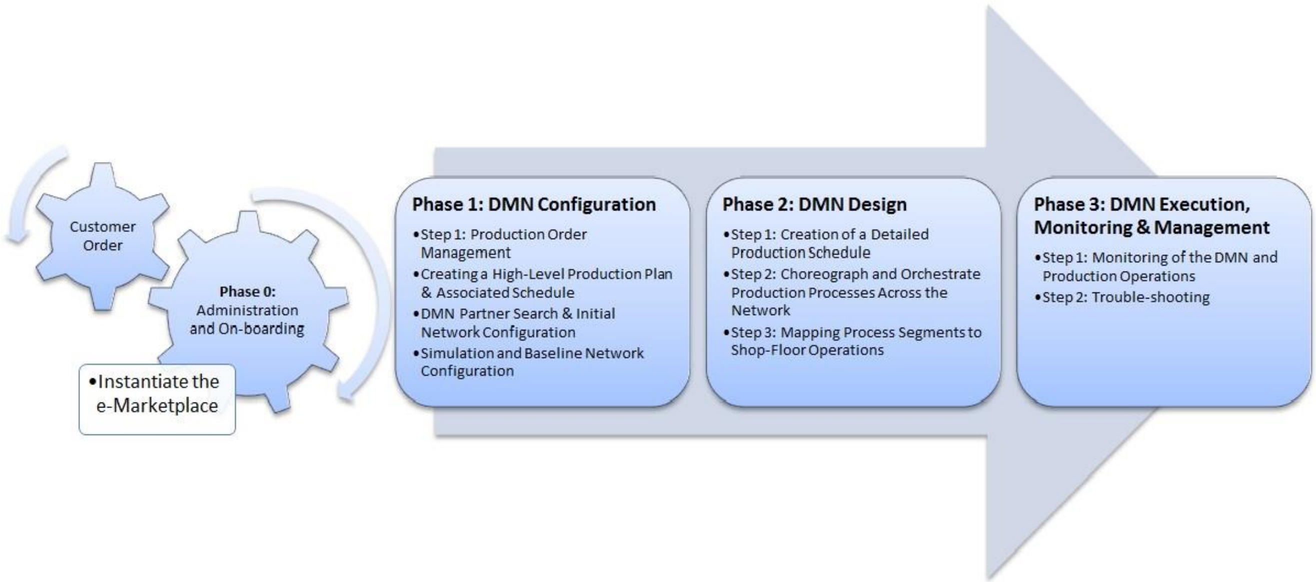

Figure 4 DMN Lifecycle (Markaki, Panopoulos, *et al.*, 2013)

2.5. Some Insights on the DMN Business Model

DMNs can be viewed as hybrid business models that reflect both some characteristics of Collaborative Networks and some characteristics of Integrated Supply Chains. Since DMNs are composed of autonomous partners, it is necessary to investigate the organizational and soft characteristics of their collaboration processes. Unlike integrated networks, partners of DMNs are more loosely coupled, with less direct interaction. However, by utilizing optimized processes and real time information sharing, they are similar, in some aspects, to integrated supply chains. In this section, we have dug deeper in Collaborative Networks, and drawn insights to assist the development of literature on the DMN business model.

2.5.1. Collaboration

Collaboration is a process in which autonomous companies share risks, responsibilities and benefits, through a joint business model that relies on information exchange, activity alignment and resource sharing, in order to achieve joint benefits and objectives (Simatupang and Sridharan, 2005a).

According to (Camarinha-Matos *et al.*, 2009), supply chain collaboration has 4 main characteristics:

- communication and information exchange;
- aligning activities and complementing goals;
- holding individual identities, as autonomous units, while being a part of the collaboration;
- joint decision making, joint goals, joint identities and joint responsibility within the Collaborative Network (CN).

The term collaboration is frequently confused and used interchangeably with other forms of supply chain integration. To clear this confusion (Camarinha-Matos *et al.*, 2009), proposed a description of different supply chain integration forms and their contents. Among different integration types, collaboration is the highest level of supply chain integration. Table 3 presents a chart that explains the content of integration in networking, coordination, cooperation and collaboration.

There have been several efforts to conceptualize and measure collaboration. (Simatupang and Sridharan, 2005b) developed a collaboration index (CI) that is composed of three dimensions: information sharing, decision synchronization, and incentive alignment. Later, (Simatupang and Sridharan, 2005a) extended the CI to five dimensions, by adding two more dimensions: collaborative performance system, and integrated supply chain processes. Depending on the configuration of these five CI dimensions, each CN can have different characteristics. Table 4 presents definitions of each collaboration dimension, and lists some of their applications.

The configuration of the collaboration dimensions should be set taking into account the requirements of the industry the DMN will operate in (Ferreira *et al.*, 2014). For instance, a DMN in the textile industry may require a lower level of integration than another DMN in the electronics industry. While a textile industry DMN selects “assisted processes” and “rough data”, an electronics industry DMN may select “real time data” and “automated processes". Also the *decision synchronization* dimension is a strategic level parameter, to be defined within the business context, e.g. being OEM-driven or SME network-driven.

Table 3 Characteristics of Supply Chain Integration Forms (Camarinha-Matos *et al.*, 2009)

NETWORKING	COORDINATION	COOPERATION	COLLABORATION
			• Joint goals • Joint identities • Working together (Creating together) • Joint Responsibility
		• Compatibility of goals • Individual Identities working apart (with some coordination)	• Compatibility of goals • Individual Identities working apart
	• Complementarity of goals (aligning activities for mutual benefit)	• Complementarity of goals • Aligning Activities	• Complementarity of goals • Aligning Activities
• Communication & Information Exchange	• Communication & Information Exchange	• Communication & Information Exchange	• Communication & Information Exchange

2.5.2. Collaborative Networks

"A Collaborative Network (CN) is a network consisting of a variety of entities (e.g. organizations, people, and even machines) that are largely autonomous, geographically distributed, and heterogeneous in terms of their operating environment, culture, social capital and goals, but collaborate to better achieve common or compatible goals, and whose interactions are supported by computer networks (Camarinha-Matos, 2009)*."*

Collaborative Networks emerged within *agile manufacturing* applications. Agile manufacturing is a paradigm that relies on dissolving the borders of companies and reaching market, on time with right products through efficient alignment of core competences (Gunasekaran and Ngai, 2004; Gunasekaran, Lai and Edwincheng, 2008). While at a strategic level, agile manufacturing counted on market clusters and strategic alliances, at an operational level, the Virtual Enterprise (VE) business model was utilized as a tool (Gunasekaran and Yusuf, 2002).

Table 4 Collaboration dimension and content (Simatupang and Sridharan, 2005a)

Collaboration dimension	Definition	Types
Information Sharing	The act of capturing and disseminating timely and relevant information	- Rough Data - Detailed Data - Real Time Data
Decision Synchronization	The way different parties manage joint decision-making in planning and operational contexts	- Centralized Decision Making - Decentralized Decision Making
Incentive Alignment	The methodology utilized to share costs, risks, and benefits between network members	- Pay for performance - Pay for effort
Collaborative Performance System	The process of devising and implementing performance metrics that guide the chain members to improve overall performance. Several systems can be utilized in order to achieve this.	- Performance assessment (ie. SCOR) - Future performance forecasting methods (ie. ANN)
Integrated SC Processes	The extent to which the chain members design efficient supply chain processes that deliver products to end customers in a timely manner at lower costs. Different levels of integration and automation can be applied according to consensus of network.	- Automated Processes - Manual Processes - Assisted Processes

Since DMNs are viewed as manufacturing industry applications of VEs, it is important to analyze the VE business model and to understand its characteristics. However, in order to have a clear analysis framework, we have adopted the classification by (Camarinha-Matos *et al.*, 2009), as presented in Figure 5.

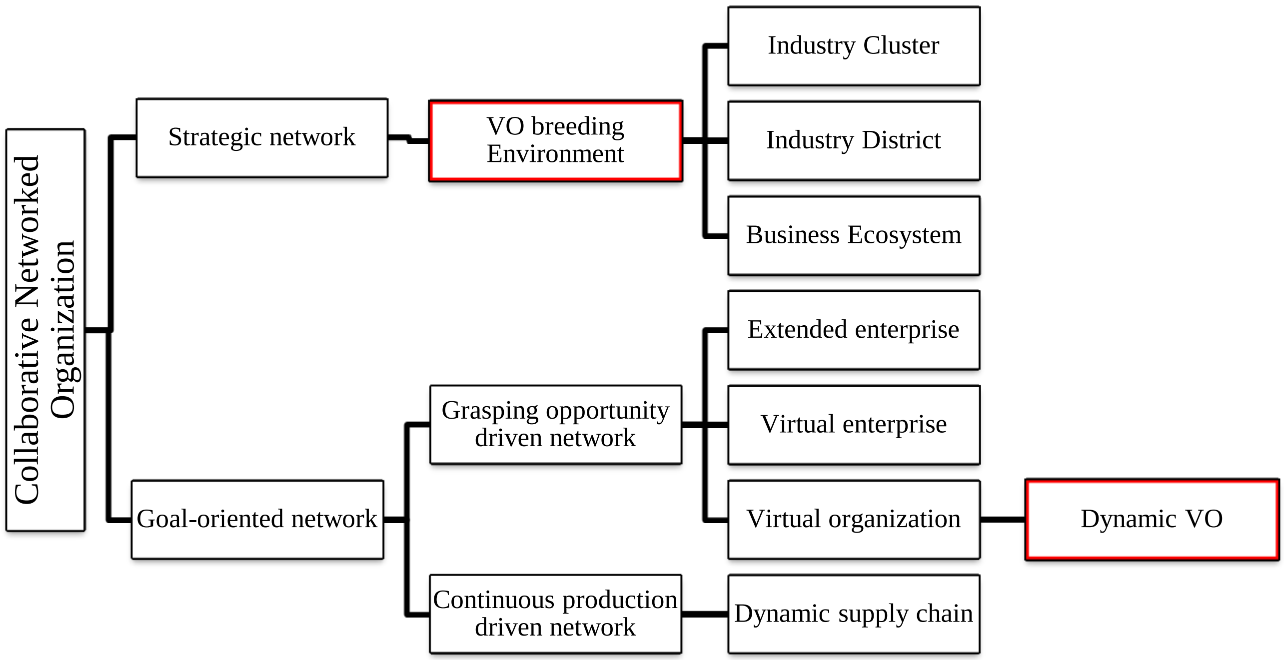

Figure 5 Collaborative Business Networks Taxonomy (Camarinha-Matos *et al.*, 2009)

A CN can either be a long-term strategic network or a goal-oriented network. *Goal-oriented networks* collaborate for a focused specific task and they reflect characteristics of cooperation more than collaboration (Camarinha-Matos *et al.*, 2009). If the goal oriented network is for a short term opportunity and is planned to be dissolved once the mission is complete, it is considered as a *grasping opportunity driven network*. These types of networks are profitable for SMEs but are very challenging to form and execute. Grasping opportunity driven networks can be Extended Enterprises (EE), Virtual Enterprises (VE) or Virtual Organizations (VO). While a *Virtual Enterprise* is a profit oriented network, a *Virtual Organization* is a network that does not specifically hold financial concerns. Thus, a Virtual Enterprise is a special case of a Virtual Organization. On the other hand, in an *Extended Enterprise*, there is a dominant company which facilitates collaboration as an extension of its supply chain.

Dynamic Virtual Organizations (DVOs) are more evolved types of VOs. DVOs are quickly formed among members of a long term strategic Collaborative Network. These types of

Strategic Networks (that are responsible for supporting and assisting DVO formation) are identified as *Virtual Organization Breeding Environments* (VBE) (Afsarmanesh, Camarinha-matos and Msanjila, 2009). A VBE is an alliance, formed of companies and related organizations, that aims to increase the overall readiness of partners for collaboration and facilitate VO formation, by setting long term collaboration agreements and providing common interoperable infrastructure and operating rules (Camarinha-Matos and Afsarmanesh, 2007). Supporting the VE business model with a VBE brings more agility and dynamism, by creating readiness for collaboration and cooperation. In Figure 5, the connection between the DVO and VBE concepts are highlighted.

VBEs can be of different types: Industry Clusters, Industry Districts or Business Ecosystems.

There are numerous real life applications of VBEs that are functioning worldwide within different industries, with different sizes and governed by different business processes and management structures. (Afsarmanesh and Camarinha-matos, 2005) present a list of VBEs with the number of members varying between 6 and 2068. These VBEs operate in many sectors in manufacturing (Mechanical, Plastic Moulds, Electronics, Textile, Mining, Process Industry, etc.), or in services (IT, Life Sciences, Telecommunications, Credit, Lending, Investments).

When the goal oriented network is not driven by a short term business opportunity but is formed in order to fulfill a long term business opportunity, it is called a *continuous production driven network* (a traditional integrated supply chain network). These types of networks, in the last decade, mutually evolved to *Dynamic Supply Chains*.

2.5.3. Classification of DMNs

It is still not clear where the DMN business model exactly fits in the CN taxonomy. (Camarinha-Matos *et al.*, 2009) mentioned a similar business model, the *Joint Resource management network*, which is characterized by resource pooling, separate ownership from management, joint (centralized) management, continuous awareness of capacities and status; but they have not further conceptualized or classified it within the taxonomy, proposing to classify these networks as VBE or Dynamic Supply Chain.

Exploring the characteristics of the DMN business model, we have distinguished two main dimensions affecting the overall organizational and collaborative structure. These two dimensions are identified as *ownership of the DMN platform* (OEM-driven or SME Network (collaboration)-driven) and *duration/motivation for DMN formation* (long term, temporary).

Considering these two classes, we have identified four different types of DMNs: VO inspired DMN; DVO inspired DMN; Dynamic Supply Chain inspired DMN; and EE inspired DMN. In terms of the ownership structure, OEM-driven and SME collaboration-driven DMNs have a considerable difference in power distribution and hierarchy. An OEM-driven DMN is formed in order to provide the DMN with a pool of potential suppliers, and typically it only considers the interests of the OEM. In this type of DMNs, partner SMEs have little bargaining power, and competition may be quite active between the partners. However in a DMN that is managed by an SME network, the joint coordination of SMEs can take decisions that bring both long and short term benefits of all partners. With this option, SMEs can gain bargaining power with the end customers, and also reach a pool of international customers, which may free them from OEM dependency.

The other collaboration dimension of the DMN business model is the duration of the DMN: whether the DMN is being formed temporarily in order to satisfy a one-time business order, or continuously, to satisfy a long term business opportunity. Even if forming a long term DMN may seem far from ideal, in practice it can be considered when working with big clients.

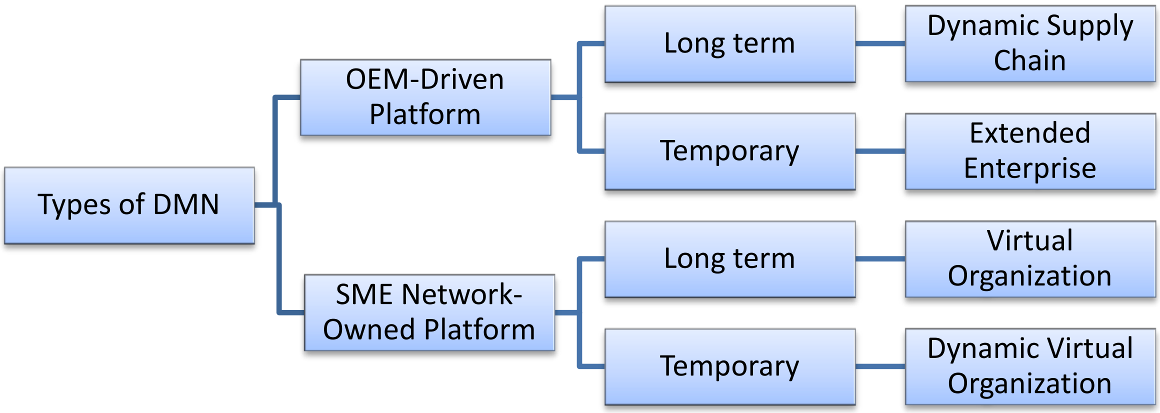

Figure 6 DMN Classification within Collaborative Networks taxonomy

According to these two dimensions, we have identified four types of DMNs can be related to four different types of CNs. Figure 6 presents the following DMN classification within the CN Taxonomy:

- a long term DMN formed through an OEM-driven platform with characteristics similar to a Dynamic Supply Chain (DSC);
- a temporary DMN formed through an OEM-driven platform with characteristics similar to an Extended Enterprise (EE);
- a long term DMN formed through an SME network-owned platform with characteristics similar to a Virtual Organization (VO);
- a temporary DMN formed through an SME network-owned platform with characteristics similar to a Dynamic Virtual Organization (DVO).

Table 5 summarizes this classification, characterizing the DMNs by defining their ownership structure, time horizon, integration type and their effects on SMEs.

Both Dynamic Supply Chains and Extended Enterprises are deployed around a leading enterprise, as it is the case in an OEM-driven platform. Unlike the SME owned platform that is non-hierarchical, these two DMN models are hierarchical, and their final goal is to fulfill the OEM objectives.

On the other hand, a long term DMN is built in order to continuously satisfy a long-term business opportunity. This can be the case when a big, loyal customer wants to have a long term contract with the network and insisting on close contact with its suppliers.

In the next section, we further investigate the different DMN types, selecting a specific business model and explaining it organizational layers. Moreover, a detailed explanation of functionalities to support each organizational layer is presented.

Table 5 Types of DMNs and their Characteristics

Type of DMN	Ownership	Time Horizon	Type of Integration	Notes on SME perspective
Virtual Organization	-SME network Driven -Non-hierarchical	Long-term business opportunity	Cooperation through Collaboration	-Too much control given to the end customer -Can create conflict within the SME network partners in terms of opportunity alignment -Can be formed for prioritized, big customers
Dynamic Virtual Organization	-SME network Driven -Non-hierarchical	Temporary business opportunity	Cooperation through Collaboration	-Full utilization of DMN benefits -More prone to disruptions and harder to operate
Dynamic Supply Chain	-OEM-driven -Hierarchical	Long-term business opportunity	Cooperation through Coordination	- Only favors the benefits of the OEM -SMEs are vulnerable in potential crisis - Can be formed for prioritized, big customers
Extended Enterprise	-OEM-driven -Hierarchical	Temporary business opportunity	Cooperation Through Coordination	-Only favors the OEM -SMEs are vulnerable in potential crisis -Hard to operate and prone to disruptions

2.6. Business Model Selection and Organizational Layers

In the business model selection process, we compare the different DMN types, according to their success in meeting a set of pre-defined requirements. These requirements were defined in the previous sections, by both considering industrial requirements and SME requirements. The comparison allows us to explicitly and objectively choose the best DMN type. DMNs are classified according to two main characteristics: ownership type and duration of collaboration. As a result of the selection process, the DVO inspired DMN type is selected as the ideal business model.

We then focus on the organizational layers of the business model: SME network and Dynamic Manufacturing Network. We provide a picture of the way the business model functions, by explaining the "SME network and DMN life cycle" and by listing SME network functions and DMN business processes.

2.6.1. *Business Model Selection*

In order to provide a comparison of different DMN types and select the most suitable business model, Table 6 was created. The first column on the left covers the business model requirements in terms of both industry and SME perspectives. As mentioned in Section 2.3.3, Discrete Complex Manufacturing Industries require the following strategies to deal with the currently existing challenges: order-driven strategy; ICT integration; Supply Chain Network wide framework; and optimization-based operational models. SME requirements were also listed as: reaching global markets; e-commerce; collaboration; process integration; sustainability; and strategic planning.

CN inspired DMN types are listed on the top of Table 6. These DMN types are classified according to their ownership type (order-driven, SME network-driven) and duration of collaboration (long term, temporary). We have evaluated each business model according to its capability of fulfilling each requirement.

In Table 6, the following notation is utilized:

√: if the business model always fulfills the requirement;

*: if the business model can fulfill the requirement only after necessary arrangements are done;

X: if the business model does not fulfill the requirement.

We have done this business model evaluation based on evidence from the literature and from observations. While a *dynamic supply chain* is classified as a continuous production-driven network and is long-term, an *Extended Enterprise* is a *grasping opportunity driven network* and temporary (Camarinha-Matos *et al.*, 2009). On the other hand, in terms of ownership style both Extended Enterprises and Dynamic Supply Chains are formed and managed by a dominant organization, and can be classified as OEM-driven. Both Virtual Organizations and Dynamic Virtual Organizations are grasping opportunity driven networks and Dynamic Virtual Organizations are specific cases of Virtual Organizations where companies quickly organize to form temporary networks.

Table 6 Business model selection for DMN types with respect to business requirements

		CN Inspired DMN Types			
Business Model Requirements		OEM Driven		SME Network Driven	
		Long Term	Temporary	Long Term	Temporary
		Dynamic Supply Chain (DSC)	Extended Enterprise (EE)	Virtual Organization (VO)	Dynamic Virtual Organization (DVO)
Industry Requirements	Order-Driven Strategy	X	√	X	√
	ICT Integration	√	√	√	√
	SC Network Wide Framework	√	√	√	√
	Optimization-Based Operational Models	√	√	√	√
SME Perspective Requirments	Reaching Global Markets	*	*	*	*
	E-Commerce	*	*	*	*
	Collaboration	X	X	√	√
	Process Integration	√	√	√	√
	Sustainability	X	X	X	√
	Strategic Planning	X	X	X	√

Compared to a Virtual Organization, a Dynamic Virtual Organization is a more agile network. Thus, among these two business models, a Virtual Organization can be classified as long-term (longer duration) and a Dynamic Virtual Organization can be classified as temporary (short duration). In terms of ownership style, both Dynamic Virtual Organizations and Virtual Organizations are formed among members of a strategic alliance, without the presence of a leading organization, and can be classified as SME network-driven.

Long-term networks, Dynamic Supply Chains and Virtual Organizations both fail to fulfill the order driven strategy requirement. ICT integration, Supply Chain Network wide framework and optimization-based operational models, requirements are all fulfilled by each DMN type. The definition of DMN does not necessarily contain the fulfilment of reaching global markets and e-commerce requirements, so there is a need for further development of necessary ICT applications. OEM-driven DMNs work according to cooperation rather than collaboration, since collaboration requires the existence of a joint identity of network members. In SME network driven DMNs, the joint identity of SMEs fulfills this criterion. Thus collaboration requirement can only be fulfilled when the DMN is SME network driven as it is the case in VOs and DVOs.

Since the DMN and the EE business models are both OEM-driven, they cannot fulfill the sustainability and strategic planning requirements. SME network driven DMNs can fulfill the sustainability and strategic planning requirements through their joint collaborative identity. On the other hand, a VO is a long-term business model that cannot be modified on the operational level in accordance with the strategic objectives. Strategic planning and long-term goal setting is pointless when it cannot be applied at the operational level. Thus, only DVO inspired DMNs can be viewed as fulfilling both the sustainability and the strategic planning criteria. The process integration criterion is naturally fulfilled by all business models due to the main characteristics of the DMN business model.

As a result of the selection process, the DVO inspired DMN business model (which fulfills all business model requirements) has been selected as the potential business model to support SMEs operating in discrete complex manufacturing industries (DCMI).

2.6.2. The (DVO Inspired) DMN Business Model

In this section of the thesis, we will explore the selected business model, namely, the DVO inspired DMN. Initially, the organizational layers of the business model will be presented.

Then, the SME network and DMN life cycle will be explained in detail. Finally, we will present the functions of the selected DMN.

In order to simplify the text, we will mention the DVO inspired DMN business model as DMN.

2.6.2.1. Organizational Layers

The business model selected to support SMEs in DCMIs has two organizational layers namely: the SME network and the DMN. While the SME network relates to strategic management and the planning level, (in Supply Chain Management), DMNs refer to operational management and the planning level (Figure 7).

In this work, we consider an SME network as a strategic partnership of SMEs.

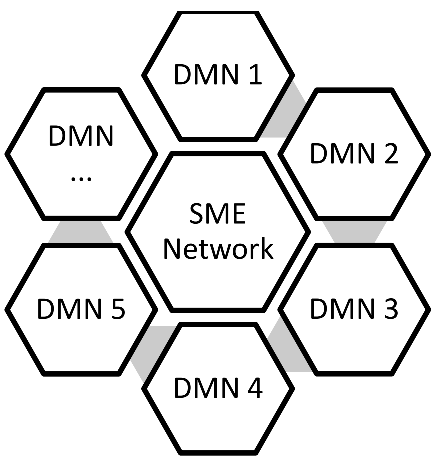

Figure 7 An SME network as the central organization and DMNs as temporary operational units formed through synchronizing SME network members

An SME network will initially provide a long term foundation for collaboration, by building the necessary agreements, rules and ICT tools. Then DMNs will be formed among SME network members. The SME network will be responsible for assisting each DMN through its life cycle.

The management of an SME network will be performed by a consortium of SME network partners. This will give each partner the right to have a word in the network decisions. The strategic decisions of the SME network will be taken through group decision making processes with collective participation of the SME network members.

While in less demanding businesses, it was initially possible to form VOs through instant networking, complex global industries require more preparedness and efficiency. As a response to these requests, strategic partnerships such as SME networks arose within agile manufacturing applications (Gunasekaran, 1998). An SME network can be defined as an association of SMEs agreeing to a long term collaboration and adopting common operating principles and infrastructures with the main goal of increasing their chances and preparedness towards participation in DMNs (Afsarmanesh and Camarinha-matos, 2005).

Strategic networks of companies to support the formation of short term opportunistic dynamic networks are the main prerequisites for agility in CNs (Gunasekaran and Yusuf, 2002; Afsarmanesh and Camarinha-matos, 2005). These networks have a potential to break the traditional myopic point of view of companies and bring a system point of view to the operation of industries (Gulati, Nohria and Zaheer, 2000). Collectively partners can compete for business opportunities that are out of their reach when they operate single handedly (Romero, Molina and Galeano, 2010).

2.6.2.2. SME network and the DMN life cycle

Figure 8 gives an understanding of how SME network processes provide a basis to enable assistance and tracking of DMN operational processes.

While the SME network formation is a onetime event, DMNs are continuously formed and dissolved within SME network members. The SME network life cycle consists of the following phases: Initiation; Foundation; Operation; Metamorphosis; and Dissolution. During the SME network foundation phase, management works on developing common processes and collaborative ICT tools. These tools will be responsible for assisting the DMN life cycle and the other phases of the SME network life cycle. The DMN life cycle phases are Creation; Operation; Tracking; and Dissolution.

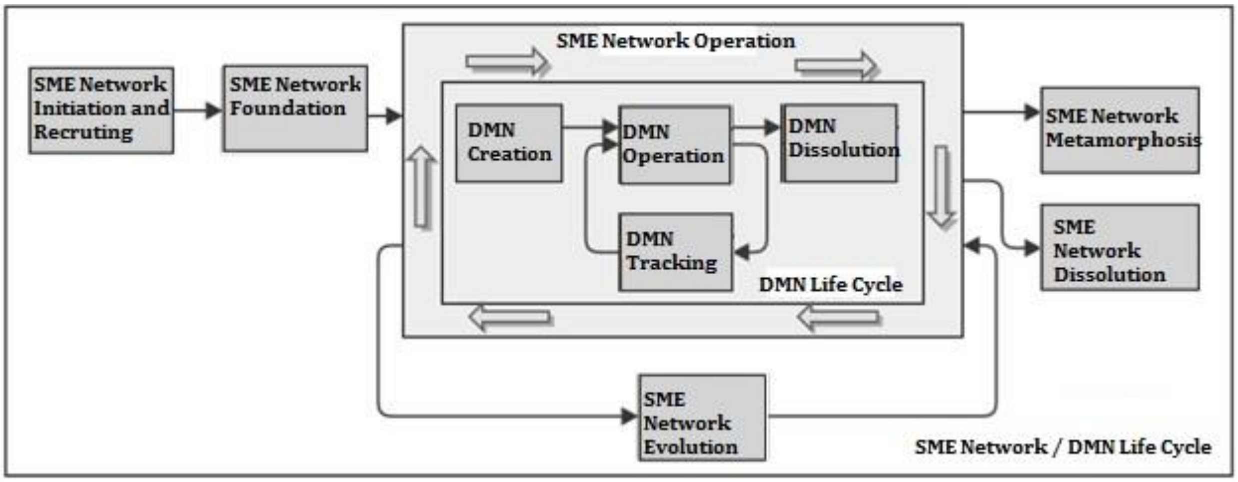

Figure 8 SME network and the DMN life Cycle (Adapted From: (Camarinha-Matos and Afsarmanesh, 2007))

DMN creation includes the formation of DMNs and planning of DMN tasks. DMN operation covers the process of DMN execution, by initiating and following the operational processes. While DMN members are implementing the DMN plan and operating accordingly, DMN tracking function occurs in parallel to DMN operation, by monitoring the execution and dealing with deviations from the initial plan, in order to ensure on time delivery to the customer. Once its mission is completed, the DMN dissolves by sharing joint benefits and costs among the members.

The SME network operation phase covers the DMN life cycle. The SME network can also go through an evolution phase, by changing collaboration rules, associating new partners or dissociating some partners. In the end of its life cycle, the SME network can either go through metamorphosis or it may decide to completely dissolve. Both of these phases need to follow predefined change processes.

2.6.2.3. Business model functions

An SME network is a special type of VBE that is composed only by SMEs. An SME network requires a collection of subsystems providing functionalities and services to assist the whole SME network life cycle, including the DMN life cycle (Afsarmanesh, Camarinha-matos and Msanjila, 2011). Due to the high level integration needs of DMN processes, partners need to share detailed and real time data through the SME network platform.

DMN by being a recently introduced and promising business model still lacks optimization-based tools, methodologies or approaches to support SME network and DMN business functions. DMNs are operational networks and their whole life cycle requires sophisticated ICT tools composed of integrated models to support several decision-making processes.

(Afsarmanesh, Camarinha-matos and Ermilova, 2008) present a VBE base functionality to support the several phases of the VBE life cycle. Since SME networks and DMNs require more tightly integrated collaboration than VBEs, processes such as production and logistics planning, scheduling and tracking need to be covered.

Putting together the information from different papers (Afsarmanesh and Camarinha-matos, 2005; Camarinha-Matos and Afsarmanesh, 2007; Afsarmanesh, Camarinha-matos and Msanjila, 2011), we came to an organized list of required functions(see Figure 9).

- **SME network initiation and recruitment:** this stage covers the initiation of the SME network by recruiting and pooling SMEs and setting up a common base infrastructure.
    - **Membership management**
    - **Collaboration support**: An SME network is composed of autonomous partners who are independent in their internal planning and management activities. However, the collaborative planning of the partners and the DMN formation process require the partners to work as a centralized network, by sharing their private data with the collaborative platform. Thus, the harmony of SME network members comes out as an important concern, since partners might be competitors outside the network. Trust, fairness and group cohesion are important goals for SME networks in order to create harmony. Therefore, it is important to provide quantifiable and comparable measures for these aspects, in the beginning of the SME network life cycle.
- **SME network foundation:** the SME network foundation phase covers the development of an ICT platform, decision support tools, and the integration of collaborative processes.

    - **Process integration:** Both functional integration between SME network partners and shop floor integration within each partner are required to set up real process integration.
    - **Development of a collaborative platform:** Software applications such as ERP or MRP II are designed for push based manufacturing, so they are insufficient in supporting order driven networks (Kristianto, Ajmal and Helo, 2011). For effective planning and management of DMNs, a customized collaborative platform is required.
- **SME network operation:** the SME network operation phase mainly covers DMN life cycle support processes. DMN requires a sophisticated collaborative ICT platform that plans and orchestrates operations of dispersed partners through the DMN life cycle (Markaki, Kokkinakos, *et al.*, 2013). The ICT platform will assist and support the automated business processes that cover DMN operations, execution, reconfiguration, cost and profit distribution, and performance measurement.
    - **DMN creation:** the DMN creation phase covers the formation and planning of DMNs. Since DMNs are fed by real time data and may use advanced planning models, in this stage decision support tools are normally required. By using the real time information shared by each partner, the ICT platform assigns at least one manufacturer to each production stage of each customer order.
        - **DMN formation:** in the DMN formation phase, DMN partners are selected among a pool of SME network partners. The most important dimension of DMN formation are the criteria/objectives used to select DMN partners. Cost and time concerns are the most commonly utilized criteria in DMN formation. However, the literature on supply chain partner selection mentions a wide list of criteria including cost, time, location, reliability, capabilities (quality, core competence, capacity, past performance), risk (political stability, economy status of the region, financial health, market fluctuations, competency), soft factors (trust, fairness, corporate culture, learning ability, personal

preferences, innovation potential) (Wu and Su, 2005; Camarinha-Matos and Afsarmanesh, 2007; Crispim and Sousa, 2009).

- **DMN production and logistics planning:** in this phase, production and logistics plans, and schedules are made. The joint production and transportation plan involves the assignment of partners to production stages, production and transportation lot sizing, raw material requirements, and production schedules.

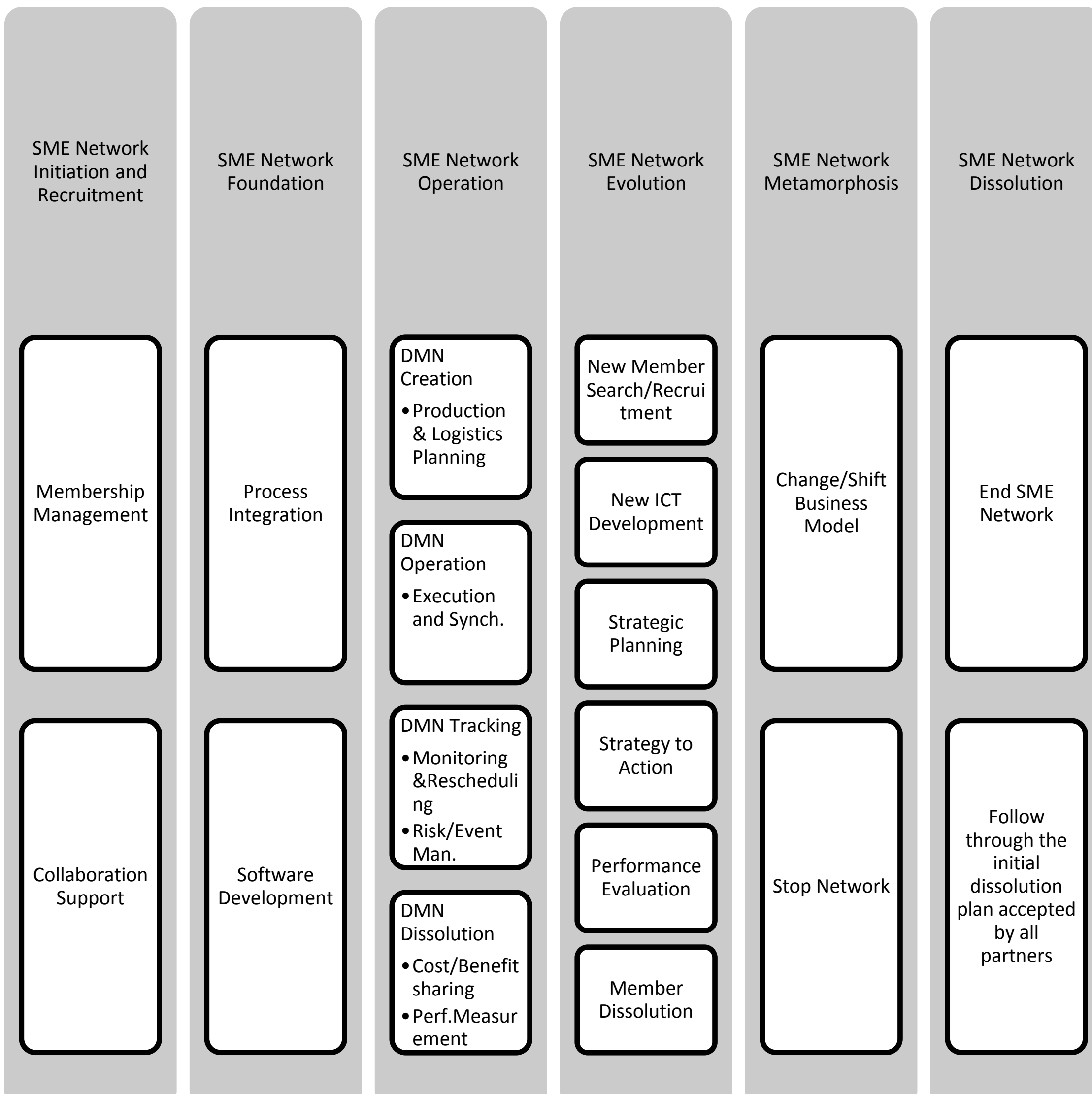

Figure 9 Functions of SME Networks and DMNs

- **DMN operation:** the DMN operation phase mainly covers the execution of DMN operational plans, tracking of DMN processes, and risk and event management.
    - **Execution and synchronization of operations:** DMNs are operational networks that are composed of autonomous companies with different goals, strategies and schedules. Lack of coordination mechanisms or support technologies in DMN management may result in conflicts and contradictions among partners, which consequently lower the entire system efficiency (Chen and Li, 2013). In the DMN operational phase each partner should follow a synchronized operational plan.
- **DMN tracking:** while DMN partners are executing the DMN operational plan, the operational process is tracked and monitored, in order to control the uncertainty arising from the autonomous and dispersed nature of partners, and to deal with possible disruptions.
    - **Monitoring and rescheduling:** order tracking and monitoring models provide visibility and reliability to support the network. Order tracking is a step in order processing that is performed to guarantee higher control over the operations. As the execution of the joint manufacturing plan starts, the platform initiates monitoring of operations and takes adequate actions in case of disruptions. Dealing with deviations from the operational plan is one of the main functions of DMNs.
    - **Risk and event management:** these functions are part of the DMN operation phase, in order to minimize the risk of delays and failure in DMN operational processes. Risk management deals with the identification, assessment and prioritization of production and transportation risks, and aims to minimize their occurrence. On the other hand, event management deals with unexpected catastrophic events, and handles their negative consequences.

- **DMN dissolution:** when a DMN fulfills a given customer order and completes the associated operational cycle, it needs to dissolve. To support this process, it is important to fairly share associated costs and benefits, and adequately measure the DMN performance.
    - **Cost benefit sharing:** joint resource management practices create joint costs and benefits that need to be fairly distributed among network members. Decision support tools need to be developed to assist the cost and benefit sharing decisions.
    - **Performance measurement:** in order to learn from member actions and fairly share short and long term benefits, partner performances need to be measured, tracked and analyzed. One of the most important dimensions in performance management is therefore, the creation of quantifiable and objective performance measures.

- **SME network evolution:** This phase covers the structural changes in the SME network. These changes include associating new members, developing new ICT applications, changing the SME network strategy and deciding the exit of members with poor performance.
- **SME network metamorphosis:** this phase is associated with a radical change shift in the SME network structure unlike the evolution phase. One of the possible forms of metamorphosis can be shifting the whole business model into another business model according to market needs. SME network management can also decide to stop the whole SME functions for a while, if required.
- **SME network dissolution:** in this phase, an SME network can finally decide to end its operations and dissolve, according to the agreements made by the partners in the beginning of the SME network life cycle.

2.7. Research Gaps and Opportunities

From this comprehensive literature review, some potential research areas in DMN and SME networks naturally emerge. The DMN business model selected in this work, requires the development of specific methodologies and decision support tools. In this phase of the research, we have focused on potential areas of research extensions that can direct the design of decision making tools and of business model integration processes.

1. **SME networks should have a clear long term objective and actionable plan**

This literature review and the identification of the potential areas of development in the new business model showed the need to develop a strong long term identity around SME networks. An SME network needs to be guided by a clear vision, accompanied by identifiable and measurable objectives, and managed by a well prepared action plan.

2. **SME networks need to develop measures to calculate partner performances**

An SME network serves customers via its joint identity of partner SMEs. A mistake made by one of the partners may result in a delay of order delivery, and may cause a reduction of the whole network reputation. Performance measures for trust, fairness and reliability of the whole network need to be created, set and tracked. The performance of each DMN partner will be computed based on its actions through different stages of the DMN life cycle. When the DMN life cycle ends, the joint benefits and costs of the network can be distributed according to the performance of partners. Moreover, these performances in former DMNs can be utilized in estimating a new DMN future performance. In the long run, successful partners can benefit from incentives and unsuccessful ones can be dissociated from the network.

3. **SME networks need to learn from the past performance**

With the development and advancement of ICT tools, networks moved from data-driven environments to knowledge-driven enterprises (Camarinha-Matos *et al.*, 2009). Therefore it is important to take advantage of the huge amount of stored data, translate it to knowledge and learn from past experiences. Data mining tools can be applied to understand patterns of SME network partners and customers.

4. **The SME network strategy and the DMN action plans need to be aligned**

The literature emphasizes the need for short term and long term strategy alignment in Collaborative Networks (Hemilä, 2010). However, in practice, companies fail to carefully plan, control and integrate these two decision levels. In the business model developed in this work, the SME network functions as the strategic unit, while DMNs are the operational units. SME networks have some long term objectives that are shared by all partners, such as sustainability, financial and market growth, and survival. It is important to translate these strategic level objectives into operational level objectives. Even though it is mainly cost that acts as an important short term objective in DMN formation, it has been clear that measures such as reliability of the network, customer satisfaction, quality or trust also have a strong impact on long term goals of SME networks.

5. **The DMN planning phase requires the development of integrated models with real time data and multiple objectives**

Holistic and integrated approaches bring numerous benefits in DMN planning, such as reduced time to market, decreased costs and increased customer satisfaction (Camarinha-Matos, 2009). However, these approaches are generally neglected in practice due to their complex nature. Recently companies are more pressured to lower their costs and maximize their operational efficiencies. Moreover, real time data on costs, capacities and inventories became naturally available, such that detailed scheduling algorithms started to be employed among supply chains. The inclusion of real life parameters, such as exchange rates and taxes, is allowing DMN planning to deal with more realistic problems.

Research directions in the DMN mathematical modeling should cover:

1. lot sizing models that provide detailed operational plans for DMNs;
2. multi objective models that are not driven by cost, but also reflect customer preferences, collaboration coherency and long term objectives.

6. **Collaboration related soft factors need to be integrated into the planning models**

In the literature, the VE creation problem has frequently been addressed as a multi criteria decision making problem rather than a pure optimization problem. VE creation requires the consideration of soft factors such as corporate culture, personal preferences and learning ability, as well as hard factors, such as utilization rates and cost concerns. Even though the DMN business model supports full integration of processes and real time information sharing, soft factors play a significant role at the SME network level. (Camarinha-Matos and Afsarmanesh, 2007) suggest that a stand-alone quantitative optimization model will not capture the matching process of potentials, abilities and subjective concerns involved in Collaborative Network formation. Social concerns such as culture, individual/group behavior, social relations or trust should be addressed in a global network modeling in order to deal with the collaborative nature of the business models under analysis (Jaehne *et al.*, 2009).

2.8. CONCLUSIONS

This study covers the development of an effective business model to support SME collaboration in Discrete Complex Manufacturing Industries (DCMI). Initially, we have identified business model requirements to support the industry characteristics, and to deal with SME challenges. Later, we have presented comprehensive reviews of the literature on DMNs and CNs, and identified four different types of DMNs as: VO, DVO, EE and DSC inspired DMNs. A business model was selected by comparing the different options and requirements. The DVO inspired DMN was considered as the best business model, in general terms.

This business model has two organizational layers: an SME network and a DMN. While the SME network is the strategic unit of the business model, DMNs are operational networks that are created and planned according to each customer order. The proposed business model supports sustainability and adaptability of SMEs, and enables SMEs to break their chains of OEM and domestic market dependency. Through e-commerce applications and a collaborative platform, the SME network will be an intermediary for SMEs to reach international business opportunities and maintain a strong joint identity.

New business models emerge every year in order to support collaboration and to increase the agility and strength of partner companies. Among these models, we believe that DMNs carry an important potential. The DMN business model is different in supporting strategic planning, allowing strategic decisions to be translated into operational actions, providing autonomous partners with a long term reliable collaborative platform, and increasing the bargaining power of partner SMEs against large international enterprises. We expect DMNs to be more commonly adopted as a business model, as ICT requirements are satisfied and more real life applications emerge.

Chapter 3: A Balanced Scorecard Approach to ICT Tools development for SME Networks

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In this chapter, we propose a new approach to ICT tools development for the manufacturing business model previously described. This model has two organizational layers; a Small and Medium Enterprise (SME) Network and a Dynamic Manufacturing network (DMN). SME Networks are Strategic Partnerships composed of autonomous SMEs who come together in order to form operational networks (DMNs). DMNs are manufacturing industry applications of Virtual Enterprises (VE) that are supported by ICT tools and automated processes, through their life cycle.

This work covers the development of a conceptual framework and the identification of functional, Informational and process flows, to support the defined business model. Initially we set an SME network vision with three dimensions; sustainability, growth, and survival. And then, we applied a Balanced Scorecard approach in to translate the SME network strategy to operational level ICT initiatives. To frame our research, we have also done a comprehensive literature review on "Tools to Support Management and Planning of Strategic Networks" and "Business Frameworks and Processes to support Operational Networks". Finally based on the guidance we have received from the literature and the established ICT initiatives, we created a set of ICT tools for the business model. These tools include a conceptual framework and the characterization of functional, informational and process flows to support the business model.

3.1. INTRODUCTION

Small and Medium Enterprises (SMEs) represent a high percentage of the world's economic power. However, they face strong challenges such as OEM and domestic market dependency. After an economic crisis, it is not likely for SMEs to bounce back as fast and as strong as multi-national global corporations. SMEs competing in discrete complex manufacturing industries are particularly challenged since they mostly lack ICT integration that is highly required by the industry. Without proper coordination and support mechanisms and integrated operational planning and control tools, it is not possible to take full advantage of networked global manufacturing (Chen and Li, 2013).

Forming collaborative networks is frequently addressed as a survival and sustainability tool for SMEs in the global markets (Camarinha-Matos *et al.*, 2009; Carneiro *et al.*, 2013). By joining their resources and competencies through networked manufacturing, SMEs can reach a larger dimension, thus allowing them to access global markets, to share risks, to nurture innovation through synergies and to increase customer satisfaction by their active involvement in product development (Afsarmanesh, Camarinha-matos and Msanjila, 2009; Camarinha-Matos, 2009; Chen and Li, 2013).

By forming strategic partnerships and short term operational networks, SMEs are able to pool their resources and maintain diversity in customers and markets. Long term Collaborative Networks supporting formation and operation of Virtual Enterprise (VE) formation are often called in the literature as Virtual Organization Breeding Environment (VBE) (Afsarmanesh, Camarinha-matos and Msanjila, 2011). Within the SME context, VBEs are called as SME networks. On the other hand, VEs operating in manufacturing industries are referred as Dynamic Manufacturing Networks (DMN). While SME networks provide the basis and long term support for inter-organizational collaboration, DMNs are formed within the members of an SME network, in order to fulfill a specific customer order.

(Coronado, 2003; Gunasekaran and Ngai, 2004) both highlighted the need to align business strategy with ICT strategy and development. On the other hand, in a business network, while ICT development follows a bottom up approach, strategy implementation typically follows a top down approach (Gunasekaran and Yusuf, 2002). In other words, while ICT development starts from the operational level and builds through tactical and strategical levels, a strategy setting starts from the strategic level and is translated to tactical and operational levels. In this context, in order to develop efficient operational level ICT tools, it is therefore required to clearly translate strategic objectives into operational initiatives.

In this work, we have initially developed an SME network vision, composed of three elements: sustainability, survival, and growth. Later we have developed a Balanced Scorecard approach to translate this vision consecutively into objectives, measures, targets, and ICT initiatives. In the following section, a literature review consisting of both methodologies to support strategic networks, and methodologies to support operational networks, is presented. Finally, taking into account the learnings from the review, a conceptual framework was developed. This conceptual framework helped us to further define the functional, process and information flows of the business model.

3.2. RESEARCH BACKGROUND AND OBJECTIVES

This section covers the business context, objectives of the study, and the methodology developed to fulfill these objectives.

3.2.1. BUSINESS CONTEXT

SME networks are strategic partnerships of autonomous SMEs that operate in order to reach joint goals. Developing DMNs through a strategic partnership is a smart agile manufacturing strategy. SME networks precede DMN formation, and they provide long term integration between network members, to support their healthy operation, to maintain trust and fairness between members, and to develop strategies to manage the operational level decisions.

The second organizational layer of this business model is the DMN. A DMN is defined as a temporary or long term collaborative network that counts on joint manufacturing efforts of geographically dispersed SMEs and/or OEMs (Viswanadham and Gaonkar, 2003; Markaki, Kokkinakos, *et al.*, 2013) A DMN is formed to satisfy a specific business opportunity (either one time or repetitive) and dissolves once the order is delivered. Figure 10 briefly presents the business model components of a DMN. While an SME network is the first organizational layer (strategic, long term) , the DMN constitutes the second layer (operational, short term) of the business model.

The "SME Network and DMN" business model functions as an intermediary between the customer and the manufacturing sides of the industry. The customer side is integrated through an e-commerce module, and a sell side marketplace is developed for customer communication. It is important to highlight that in this business model, SMEs face customers collectively, via the SME network joint identity. On the manufacturing side, DMN formation and operational planning require integrated business processes and an automated, collaborative ICT platform. This collaborative platform needs to be built in order to assist the DMN life cycle, to support SME network decision making, and to monitor order processing. The collaborative platform can simultaneously be used by several DMNs that are designed to fulfill different business opportunities.

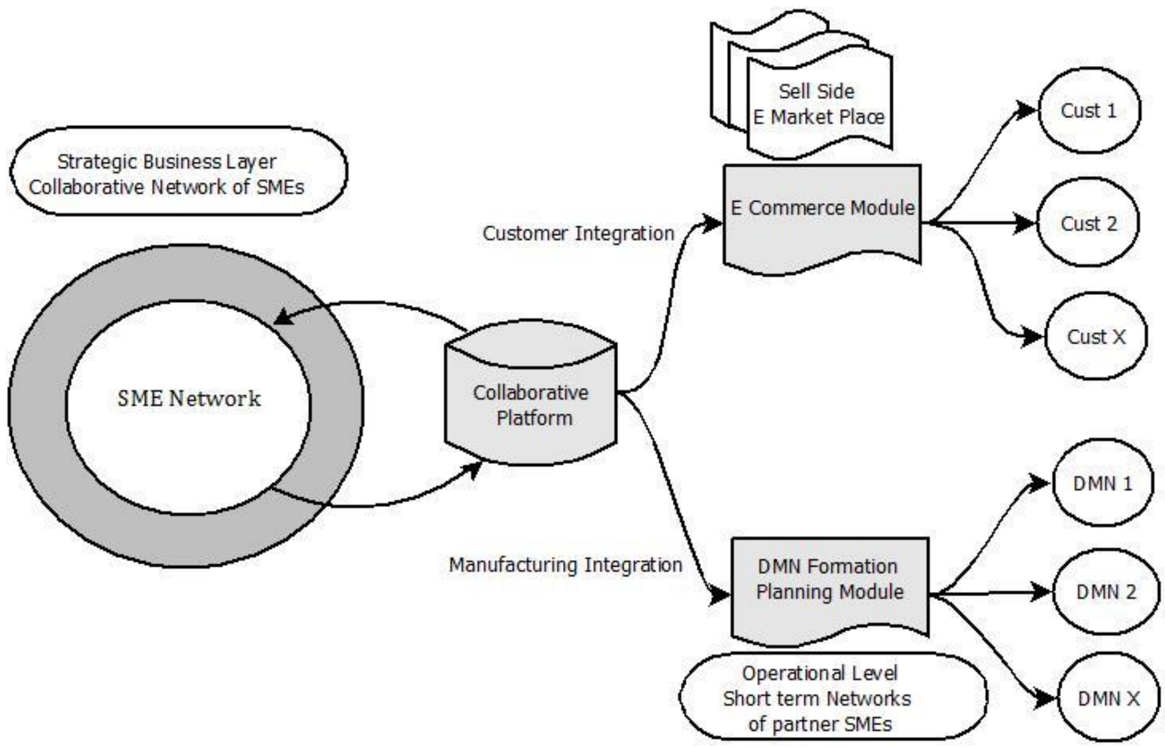

Figure 10 SME network and DMN business model

Typically an Enterprise Resource Planning (ERP) only provides functional integration at the factory level. However a manufacturing network requires further inter organizational integration between autonomous partners (Chen and Li, 2013). ERP applications provide control over shop floor operations but they do not provide a means to link the autonomous network members. The required ICT framework should both link demand and manufacturing planning, and should integrate the different network members (Van Assen, Hans and Van de velde, 2000). Moreover, the development of ICT tools is necessary to decrease decision making time and increase operational efficiency (Chen and Li, 2013).

3.2.2. Research Objectives and Methodology

These business networks require automated processes to assist the DMN life cycle, and the business functions to support SME network decisions. A DMN works at the operational level and requires detailed focused decision support tools to enable and optimize its operations. In this context, an ICT system should both support the back end and the front end of the whole supply chain, should facilitate interoperability among autonomous members, should enable communication flows within the network, and should assist business processes through the DMN life cycle (Liu, Zhang and Hu, 2005).

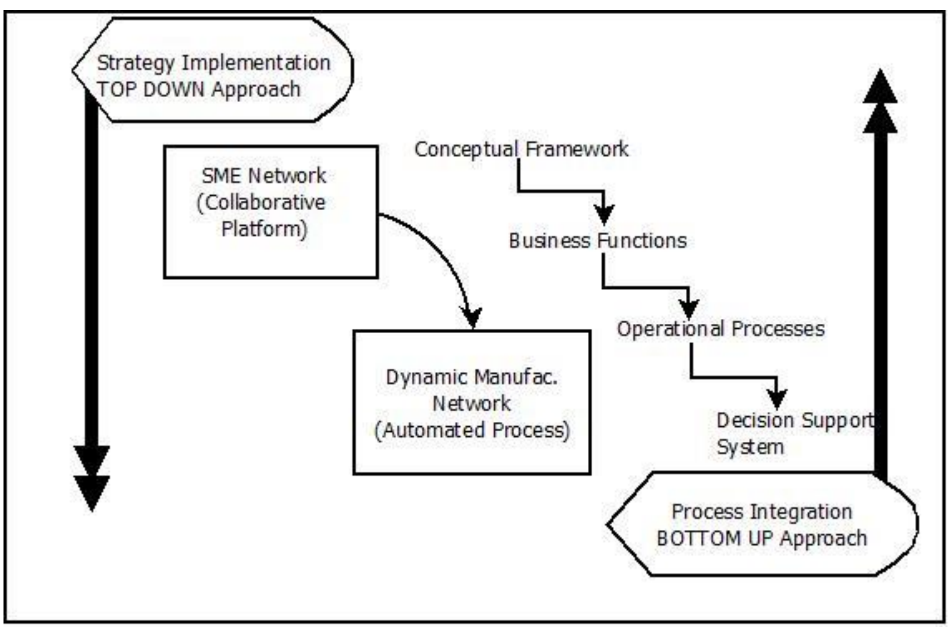

Figure 11 Strategy implementation steps for the business model

In order to develop such a system, sound business and ICT strategies are required. In ICT design, standardizing and integrating heterogeneous ICTs of network members, under a common framework, is the primary task (Coronado M, Sarhadi and Millar, 2002). The initial step of the ICT integration includes integrating the operations of each network member. The second step covers network wide integration, via the common platform. While a bottom up approach may be utilized for process integration, in strategy generation and implementation, a top down approach is in general preferred (Gunasekaran and Yusuf, 2002). Process integration starts with integrating each partner's internal processes and linking those processes through a collaborative platform. On the other hand, strategy implementation starts from strategy setting of the SME network, and extends to translating the higher level strategy to tactical and operational actions.

Several researchers have discussed the need for alignment of the business strategy and the ICT strategy. (Coronado, 2003) claims that identifying a sound business strategy is the key for business process agility. To successfully support business processes, the ICT strategy also needs to be aligned with the business strategy. (Gunasekaran and Ngai, 2004) state that an automated network needs to initially define its business requirements which will lead to a business architecture to be further supported by an ICT infrastructure. Business model development and goal setting are clearly the basis for developing a correct information technology infrastructure.

Figure 11 presents a set of strategy implementation steps for the business model. While strategy development needs to start at the strategic level, by SME network goal setting and strategy setting, process integration needs to start at the operational level by developing a set of automated collaborative processes. In terms of process integration, as we go from bottom to top, the level of integration decreases and tools move from detailed mathematical decision support systems to conceptual frameworks or reference models. On the other hand, in terms of strategy setting, decision makers need to first decide the strategy of the SME network and later, develop ICT tools at the operational level, by translating that strategy to operational goals. In order to create successful collaborative networks, the business strategy should be integrated into the development of ICT tools and decision making methodologies.

As referred above, the objective of this part of the wok was to develop ICT tools to support "SME network and DMN" business model. Initially we need to define an SME Network vision, and translate it into ICT strategies. Moreover, it is also necessary to anticipate ICT applications to guide the development of ICT tools.

In order to fulfill these needs, the SME network vision is initially grounded on three components: sustainability, survival, and growth. This vision is then translated into operational level ICT initiatives through the Balanced Scorecard methodology. In the ICT tools development phase, first SME network business functions are identified and the elements are listed in a conceptual framework. Then, functional, informational and process flows of the system are defined. These tools will guide the development of more focused decision support tools for each function of the business model.

Figure 12 presents the adopted research methodology. To start with, we have defined the business model as an SME network at the strategic level, and a DMN at the operational level. Later, we have developed a vision for the business model with a detailed identification of the vision components. Then we have implemented a Balanced Scorecard on the SME network strategy and vision, to define objectives and actions for the business model and to find out interesting ICT initiatives. This research was based on a comprehensive literature review on "tools to support management and planning of strategic networks" and "business frameworks and processes to support operational networks".

In the ICT tools development phase, we have first created a conceptual framework that consists of modules and submodules, required to support the business model. Finally, we have defined the functional, process and informational flows that explain how business model functions are associated with each other, and how they are connected through information sharing.

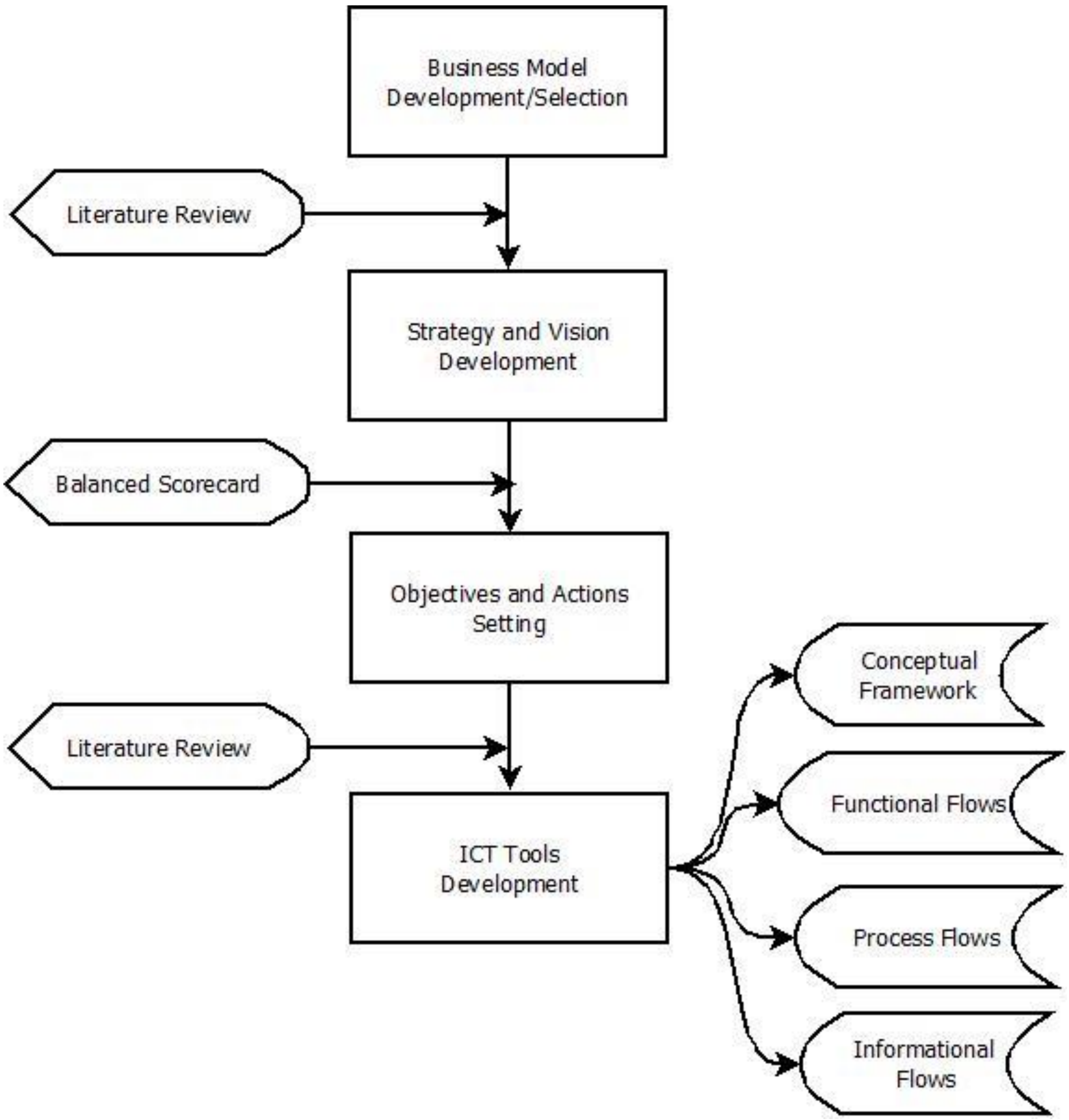

Figure 12 Research Methodology

3.3. TRANSLATION OF THE STRATEGY TO ICT INITIATIVES

In order to identify the SME network vision, we have investigated possible gains of SME collaboration and its limitations, considering the different dimensions involved. We have then implemented a Balanced Scorecard translated each dimension into specific ICT initiatives.

3.3.1. SME NETWORK VISION

The components of the SME network vision were defined as sustainability, survival, and growth. While *survival* is the act of standing against economic crisis and other disturbances in the system, *sustainability* stands for withstanding internal organizational challenges. *Growth*, on the other hand, stands for the expansion of the SME network along time.

SMEs, when they operate alone, tend to have small market shares and few major customers. They normally serve a small number of big customers by which they are dominated and that decrease their bargaining power (Levy, Loebbecke and Maier, 2003; Noori and Lee, 2006). One of the main drawbacks of serving a small number of customers is the risk associated with the loss of customers. Increasing market share and maximizing customer variety will decrease the power each customer has on SMEs (Levy, Loebbecke and Maier, 2003).

Individually, SMEs fail to participate in global competition. However, through collaboration, they can increase their scale and grow by expanding their product portfolios and encouraging innovation (Levy, Loebbecke and Maier, 2003; Camarinha-Matos *et al.*, 2009). Moreover, SMEs can increase their collective capabilities, by taking advantage of their ability to select the most efficient production path for each order (Noori and Lee, 2006). Thus one of the main objectives of SME networks is growth, in terms of both market share and customer variety.

On the other hand, survival of the SME network collective and its partners individually also comes out as one of main reasons for collaboration. Unlike traditional fixed supply chains, SME networks have the ability of self-organization, dynamism and adaptation to ever-changing circumstances, by forming DMNs (Noori and Lee, 2006). In order to survive in today's turbulent markets, companies need to continuously adapt the business environment network structure to the changing economic, social and cultural conditions (Lin and Zhang, 2005; Camarinha-Matos *et al.*, 2009). Collaboration and adaptation will increase the competitiveness of the whole network and increase survival chances of each network partner.

Collaboration has various, clear benefits for each partner and for the network. However, the sustainability of a collaborative network has some associated risks, due to the competitive nature of its members. Even though collaboration is supported through network wide ICT tools, partners still compete in other supply chains they are involved in, possibly conflicting objectives. In order to maintain sustainability in the long term, the network has to identify risks that can threaten group harmony and develop remedies to overcome these obstacles (Camarinha-Matos *et al.*, 2009). Therefore, there is a clear need for objective measures to compute and to track the fairness of the collaborative network, and to find sharing mechanisms that can determine each participant's contributions and benefits. Perhaps, measuring network performance will give network members confidence over the benefits of collaboration (Camarinha-Matos *et al.*, 2009).

The main reasons behind SME collaboration are growth and survival (Svensson and Barfod, 2002; Lin and Zhang, 2005; Camarinha-Matos, 2009). Because of their small scale and isolation from international markets, when they operate alone, SMEs are weak and vulnerable compared to large corporations (*Annual Report on European SMEs*, 2013). By pooling resources and sharing risks, SMEs increase their chances of market growth and survival, in case of a potential crisis. The success of the network is not only threatened by external factors but also by internal risks that are related to competition between the network partners. Thus, another important concern in SME collaboration is the sustainability of the network, in terms of providing balance and harmony between partners (Camarinha-Matos *et al.*, 2009).

3.3.1.1. Sustainability

Collaboration strategy brings many long term joint benefits to the network, such as synergy, collective competitiveness and innovation. In order to join a collaborative network, a company should perceive these joint benefits as being more important than its own short term gains or opportunism (Bengtsson and Kock, 2000).

Each partner of an SME network is autonomous, and partners are possible competitors outside the network. Under these circumstances, sustainability of an SME network highly relies on group harmony and cohesion. It is important to initially prevent conflicts between network members, and then provide conflict resolution tools for possible emerging problems.

Group cohesion consists of elements such as trust, fairness, sharing, reliability and visibility (Camarinha-Matos, 2009; Romero and Molina, 2009). In order to maintain the SME Network operating properly in the long run, control mechanisms should be developed to quantify, measure, and balance these soft factors. Trust is often highlighted as the main driver for group cohesion within an SME network. Trust is defined as the willingness of the partners to take the risk for sharing information, materials, customers, etc. (Jaehne *et al.*, 2009). Problems with trust can create a strong barrier to information sharing in a manufacturing network (Piramuthu, 2005). Therefore, in collaborative network planning, we need to initially provide a common understanding of trust within the network, and later continuously support and assure its existence to all parties.

Another important sustainability concern for collaborative networks of profit oriented organizations is building safe and fair "sharing and allocation mechanisms" (Viswanadham and Gaonkar, 2003; Camarinha-Matos *et al.*, 2009). Carefully designed decision support tools can play an important part for this purpose, guaranteeing fair distribution of both costs and benefits of the SME network. The principles and measures for fair distribution have to be agreed by all parties.

Another drawback of collaborative networks is the fact that one member's failure in its internal operations can jeopardize the whole network's reputation. Reliability measures and control mechanisms may help the network in developing an understanding of each partner's network performance. Moreover, mechanisms should be deployed to help predicting partners' and network's performances by using past performance results. In some sense, reliability stands for how much the SME network can collectively rely on each partner's performance.

3.3.1.2. Growth

In general, SMEs, when operating alone, do not hold the competency and know-how required to reach international markets. Due to this drawback, they mainly operate in safe niche markets or join OEM driven supply chains (Char, Yasoa and Hassan, 2010). They also lack the strategic planning necessary for growth in the long run. Joining collaborative networks offers SMEs an opportunity to reach big markets that are beyond their individual scale, and to be a part of a growing and an expanding community.

Moreover, individually, SMEs lack the necessary ICT tools and automation, necessary for manufacturer and customer integration, but an SME network platform can provide a means of integration and can allow dynamic and agile formation of manufacturing networks. However, in order to adopt an SME network platform, SMEs are still required to improve their operations and integrate their own processes. An SME network platform would surely extend their intra organizational integration to inter organizational integration.

Joining a Collaborative Network usually brings considerable growth to all members, in several financial and potential areas, such as market share, competitiveness, brand development, ROI, stock value, etc. (Camarinha-Matos, 2009). However, SMEs should be aware of the need to invest in the network and to wait for the longer term benefits to appear.

3.3.1.3. Survival

SME networks inherently bring *survival* benefits to SMEs (Camarinha-Matos, 2009). Through a scale increase, SMEs can improve their capability to withstand sudden external challenges such as catastrophic events and economic crisis. The tremendous financial problems SMEs faced during the recent crisis were mainly due to their OEM dependency and domestic market dependency (*Annual Report on European SMEs*, 2013). While large corporations managed to deal with these financial challenges by operating in alternative markets, OEM and domestic market dependent SMEs mostly went bankrupt. Since SME networks create alternative markets and increase overall bargaining power, partner SMEs also individually become more resilient in terms of crisis.

Another dimension of *survival* is the ability to learn from past data and dynamically adapt to outer and inner challenges (Camarinha-Matos *et al.*, 2009). To cope with these problems, companies can take advantage of stored data, translate it to knowledge and learn from past experiences. Data mining and knowledge extraction tools can surely be very useful to understand partner and customer behavioral patterns.

Moreover, survivor is strongly linked to adaptability. Adaptability is the ability to measure and track system performance and adjust it when necessary (Ivanov, Sokolov and Kaeschel, 2010). In order to be more adaptable, a manufacturing network needs to align strategy with operations. This means, strategy should be aligned between the partners and between the SME Network and the partners.

Finally, another solution for SME network survival lies in investing in Research and Development (R&D). The Collaborative Platform proposed in this work, should have a key role in assisting collaborative research and development processes and supporting the network members to be innovative. Moreover, through developing branding and marketing solutions, the SME network can strengthen its own identity and its resilience.

3.3.2. Implementation of a Balanced Scorecard

The "SME Network and DMN" business model is an ICT dependent business model managed by an automated Collaborative Platform. Our main goal in this work is to translate the SME network vision to ICT initiatives that can shape the development of the Collaborative Platform.

The Balanced Scorecard (BS) framework has been widely used as a strategic management tool. Since it was proposed in the 1990s, it is has been used to measure and manage four aspects of organizational performance: Financial, Customers, Internal Business Processes, and Learning and Growth (Al-ashaab, Flores and Magyar, 2011). BS allows decision makers to extend their myopic, only financially focused-perspective, to other decision dimensions and stakeholders. In BS development, all four perspectives are guided through four major steps:

1. objectives clarify the company vision and translate it into a strategy;
2. measures provide quantitative indicators for each objective, and allow decision makers to link objectives with results;

3. targets allow decision makers to set specific goals, through long term or short term quantitative or qualitative goals;
4. initiatives recommend some actions that can be taken in order to reach identified targets for each objective (Al-ashaab, Flores and Magyar, 2011).

We have adapted the BS methodology by focusing on our three different vision components: sustainability; growth; and survival (See Figure 13). We have connected each vision to one or more balanced scorecard perspective as follows: Sustainability to internal business processes perspective; growth to customers and financial perspectives; and survival to learning and improvement perspectives.

The BS application of each SME Network vision component is briefly explained in the following sections.

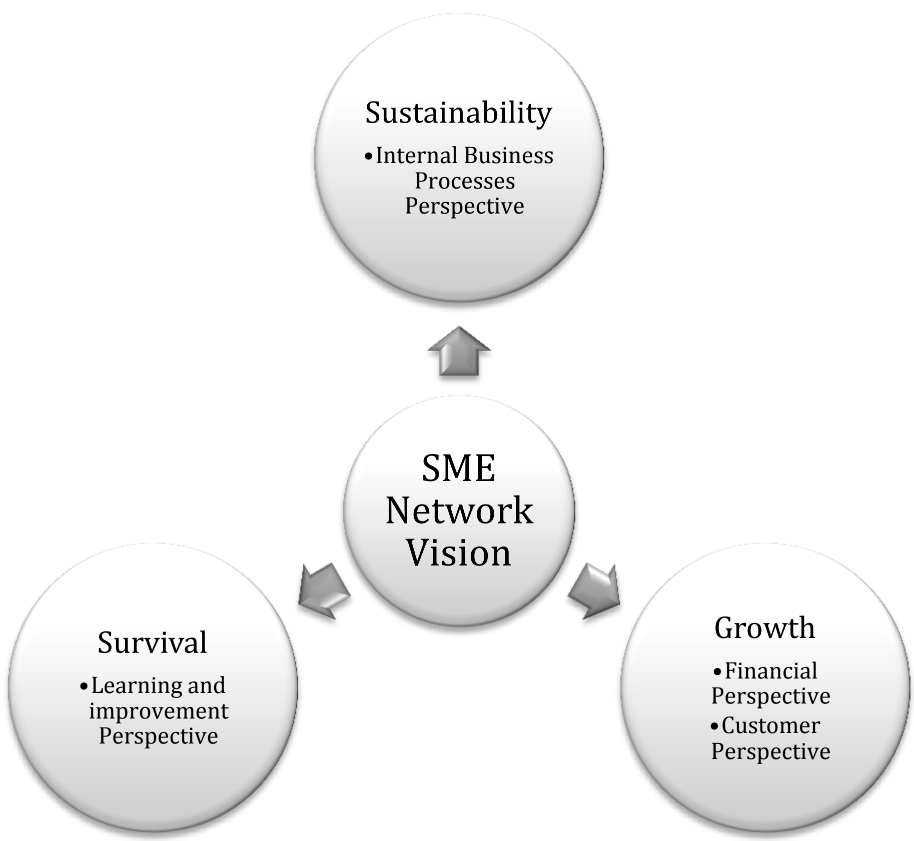

Figure 13 SME network vision and the Balanced Scorecard perspectives

Following research questions guided the translation of objectives to IT initiatives:

- How can we reach this objective through IT strategies?
- Which types of ICT Tools we can build to reach this objective?
- What can be a possible ICT strategy to reach this objective?

3.3.2.1. Sustainability Balanced Scorecard

Through the sustainability BS, we can derive a list of ICT initiatives that need to be implemented in order to reach the vision. Table 7 presents the developed Sustainability BS. In order to maintain the group cohesion and harmony required to sustain the collaborative network, the following sustainability objectives were developed: supporting conflict resolution between members; establishing high trust value, establishing high reliability value, establishing high fairness value and providing a membership management function.

Table 7 Sustainability Balanced Scorecard

SUSTAINABILITY					
	OBJECTIVES	**MEASURES**	**TARGETS**	**IT INITIATIVES**	**ICT TOOLS**
Internal Business Processes Perspective	Support Conflict Resolution between members	Visibility of Operations	none	Provide reporting for SME network decisions	**Reporting**
		Develop Initial aggrements	none	Prevent possible future conflicts by developing initial aggrements	**Membership Management**
	Establish High Trust Value within network	Trust of partners to the SME Network	max	Set and track trust measures between partners and the SME network	**Trust Management**
		Trust between partners	max	Set and track trust measures between partners	**Trust Management**
	Establish High Reliability Value	Reliability of logistics	max	Set and track reliability measures for logistics operations	**Reliability Management**
		Reliability of raw material	max	Set and track reliability measures for raw material received from suppliers	**Reliability Management**
		Reliability of the ICT Platform	none	Provide security mechanisms for the ICT Platform	**ICT Platfrom security**
		Reliability of data	max	Set and track reliability measures for the data received from partners	**Reliability Management**
	Establish High Fairness Value	Fairness of the SME Network	max	Set and track fairness measures for SME network joint functions	**Fairness Management**
		Fairness in demand sharing	none	Develop fair demand sharing mechanisms	**Demand Sharing**
		Fairness in revenue sharing	none	Develop fair revenue sharing mechanisms	**Revenue Sharing**
		Fairness in cost sharing	none	Develop fair cost sharing mechanisms	**Cost Sharing**
	Provide Membership Management	Member Profiling	none	Develop member performance Module	**Performance Management**
		Membership Management	none	Develop member association and dissociation Module	**Association Dissociation and Decision Making**

These objectives have guided us to identify the following ICT initiatives: set and track measures for each group cohesion component; provide reporting for network decisions and actions; develop pre-membership agreements; develop fair sharing mechanisms; develop member performance module; and develop a member association/dissociation DSS.

3.3.2.2. Growth Balanced Scorecard

Table 8 presents the developed Growth BS that consists of two different perspectives: Customer and Financial. The customer perspective considers five different objectives namely: maintaining high customer satisfaction, minimize the number of returning customers, minimize the value of returning customers, maximize customer loyalty and maximize market share. The IT initiatives are also mainly identified as follows: planning and tracking of DMN through its life cycle, tracking and assessing DMN performance, development of an e-commerce module, developing Customer Relationship Management tools; developing an order promising system, and developing a finance function.

3.3.2.3. Survival Balanced Scorecard

The survival Balanced Scorecard consists of objectives for the learning and improvement objectives (see Table 9). The objectives are the following: automation of business processes; establish adaptability in DMN composition; establish tracking in DMN operations; establish rescheduling in DMN; establish strength in technology; increase the number of new products; increase the number of new patents; support brand development; and support strategic planning.

These objectives lead to focusing the following initiatives in ICT development: developing automated Decision Support Systems for DMN functions; developing risk and event management tools for DMN; developing performance measures for DMN, developing monitoring and rescheduling modules for DMN; supporting process integration for each partners internal processes; supporting customers feedback; developing a collaborative product development platform; developing collaborative decision making tools; developing brand management and advertising functions; creating a strategic planning function.

Table 8 Growth Balanced Score Card

GROWTH						
		OBJECTIVES	**MEASURES**	**TARGETS**	**IT INITIATIVES**	**ICT TOOLS**
Customer Perspective	**1**	Maintain high customer satisfaction	Number of complaints	min	Develop online platform for customer complaints and their resolution	**Customer Relations module**
	2		Customer response time	min	Develop automated DMN formation and planning modules	**DMN Formation and DMN Operational Planning**
	3		Support real time information sharing	none	Develop necessary infrastructure for real time information sharing	**ICT Platform information sharing**
	4		On time delivery ratio	max	Track orders through their production and transportation, develop Risk and Event Management modules	**DMN Tracking/ DMN Risk Management/ DMN Event Management**
	5		Zero defect orders	max	Track quality performance of partners	**DMN Performance Assesment**
	6	Minimize Rejected Orders	Order acceptance ratio	max	Develop e-commerce module and order promising process	**E-Commerce Module and Order Promising System**
	7		Number of rejected orders	min	Track rejected orders per customer, create mechanisms to control rejection frequency	**Customer Tracking and Order Acceptance**
	8		Value of rejected orders	min	Prioritize orders according to value and Develop Order Selection and Acceptance Modules	**Order Prioritization and Order Acceptance**
	9	Minimize Rejected Customers	Value of rejected customers	min	Develop customer segmentation and prioritization models	**Customer Segmentation and Customer Prioritization**
	10		Customer Acceptance ratio	max	Develop pricing strategy for different customers and negotiate for alternative order delivery parameters	**Customer Relations Module**
	11	Maximize Customer Loyalty	Average customer service Time Span	max	Develop customer relations module	**Customer Relations Module**
	12		Number of orders received per customer	max	Track customer orders and value, Develop Decision Support Tools to figure out Customer and Order Patterns	**Customer Tracking/ Customer Segmentation**
	13	Maximize Market Share	Market share for each product	max	Support opportunity search for each product	**Opportunity Search**
	14		Market share for each industry	max	Support opportunity search for each industry	**Opportunity Search**
Financial Perspective	**15**	Maximize Financial Measures	ROI	max	Track ROI	**SME Network Performance Management/ Finance**
	16		ROA	max	Track ROA	**SME Network Performance Management/ Finance**
	17		Profitability	max	Track Profitability and prioritize profitable orders	**Order Prioritization/ Finance**
	18		Stock Price	max	Track Stock Price	**SME Network Performance Management/ Finance**

Table 9 Survival Balanced Scorecard

	SURVIVAL				
	OBJECTIVES	**MEASURES**	**TARGETS**	**IT INITIATIVES**	**ICT TOOLS**
Learning and Improvement Perspective	Automation of Business Processes	Number of automated Decision Modules	max	Develop automated processes for DSS functions	**ICT Platform**
	Establish adaptability in DMN composition	No Measure	none	Develop Risk Management Module	**DMN Risk Management**
		No Measure	none	Develop Event Management Module	**DMN Event Management**
	Establish learning in DMN formation	No Measure	none	Develop performance measures for DMNs	**DMN Performance Assesment**
	Establish tracking in DMN operations	No Measure	none	Develop monitoring module for DMNs	**DMN Tracking**
	Establish Rescheduling in DMN	No Measure	none	Develop rescheduling module for DMNs in order to deal with disrupted orders	**DMN Crisis Management**
	Establish strength in Technology	No Measure	none	Support process integration and ICT development for each partner internal processes	**ICT Development**
	Increase number of new products	Number of new products per year	max	Provide collaborative platform for new product development	**Collaborative Product Development**
	Increase number of new patents	Number of patents per year	max	Provide Collaborative platform for new product development	**Collaborative Product Development**
		Average increase in number of patents per year	max	Support customer feedback and opinion on new product ideas	**Customer Relations**
	Support Brand Development	Increase number of international brands	max	Support Communication to develop brand management strategies	**Brand Management**
			max	Support communication to develop advertising strategies	**Advertising**
	Support Strategic Planning	Develop Long Term strategy	none	Support communication on Strategic Planning	**Strategic Planning**
			none	Track long term goals	**Strategic Planning**
			none	Support and control alignment of strategy with operations	**Strategic Planning**

3.4. ICT TOOLS TO SUPPORT STRATEGIC AND OPERATIONAL NETWORKS (A LITERATURE REVIEW)

In this section, a literature review on ICT tools to support collaborative networks is presented. Collaborative Networks have been classified into two main groups, based on their organizational structure: Strategic Networks and Operational Networks (Camarinha-Matos *et al.*, 2009). Strategic Networks are generally referred as Virtual Organization Breeding Environments (VBE) and they form a collaboration basis to support the foundation and functioning of operational networks. Many different organizational forms have emerged among operational networks, such as Virtual Enterprises; Dynamic Virtual Organizations; Networked Manufacturing; Dispersed Manufacturing Networks; and Dynamic Manufacturing Networks. Since the level of integration is higher in operational networks than in strategic networks, the former have more automated and detailed ICT tools.

The main objective of this section is to understand the state-of-the-art in ICT for Strategic and Operational Networks and try to identify the main research gaps in the area. The findings of this literature review will hopefully guide us in the development of new ICT Tools.

3.4.1. Tools to support management and planning of Strategic Networks

Here, we will focus on frameworks and generic models to support VBEs. While operational network planning and management are clear functions of Strategic Networks, there are naturally other tasks and processes required to keep the network operating.

Reference models, conceptual frameworks and system architectures are common planning concepts to assist VBEs at their planning and management. These methodologies provide an overall picture of the VBE management system and enable the development of business functions and ICT tools. (Camarinha-Matos and Afsarmanesh, 2008) defined these terms as follows:

- Once established, a reference model serves to understand the different manifestations of a new paradigm, at the abstract level, by providing a common basis. Reference models provide guidance to develop more concrete models to support Collaborative Networks. Before looking at specific decision support modules, it is important to understand the high level needs of the business model, and to customize the support processes according to the business model objectives.
- A conceptual framework draws the outline for business models by defining a number of sub-models, collections of templates, procedures, methods, rules and tools.
- A system architecture is a composition of the different modules of a particular system, including its system structure, functions of its components, their interactions and constraints.

(Afsarmanesh and Camarinha-matos, 2005) proposed a conceptual framework to give an initial picture of elements and requirements of a VBE support management system. Apart from defining base functionalities to support the DMN life cycle, they also defined the VBE management requirements as: Competencies Management; Value Systems; System of Incentives; and Trust Management. A supply chain management system that is based on an inter-enterprise work flow architecture was developed by (Liu, Zhang and Hu, 2005). The interface assists outsourcing, sales, inventory planning, production planning, and customer service decision making through autonomous agents.

Later (Camarinha-Matos and Afsarmanesh, 2007) developed a new conceptual framework to support Virtual Organization creation in a breeding environment. The system has four other modules namely: supporting information management; VBE structure and membership management; profiling and trust management; and VBE management decision support system. (Chae, Choi and Kim, 2006) proposed an architecture framework for a collaborative manufacturing context. The framework is modeled using object oriented and fact-oriented methods. Later they provided an example with an Enterprise Architecture for a supply chain based on Supply Chain Operations Reference (SCOR) model. (Varvakis, 2007) proposed a conceptual framework to create and support the lifecycle of a VE within a VBE the in mold and die sector. The proposed framework has been validated in a Brazilian VBE called Virfebras. (Camarinha-Matos and Afsarmanesh, 2008) presented a reference model -for collaborative networked organizations- that synthesizes and formalizes concepts, principles, and recommended practices. (Carneiro *et al.*, 2013) proposed a collaboration reference model for customized products, and tested the methodology by applying it to two networks from the fashion industry. The model supports collaborative processes by providing a conceptual framework that defines business processes required to assist the main operational activities.

(Romero and Molina, 2009) developed a VBE and VO Integral Business Process Management framework that defines a set of process models describing each VBE and VO management process. (Oliveira and Camarinha-matos, 2012) presented an integrated architecture to support negotiation in order to form VOs through VBEs. The architecture has modules such as partner search, negotiation for VO formation, data bases and VBE information system (Profile, Competencies and Trust).

On the other hand, some researchers have focused on the performance of strategic networks in the long run, and developed several simulation and mathematical models for measurement purposes. (Duin, 2007) came up with a simulation model for long term enterprise networks that act as VBEs. A game based model was developed to evaluate the impacts of different strategies on the organization. This is one of the few papers to simulate strategies in VBEs. (Ivanov, 2010) created an adaptive framework that assists supply chain design and aligns strategic, tactical and operational level decisions. The developed mathematical framework is composed of several model blocks and it functions as an optimization and simulation engine, in an informational architecture. (Ivanov, Sokolov and Kaeschel, 2010) proposed an adaptive supply chain framework with structure dynamics considerations. They have considered a supply chain as a complex multi structural system, and modeled it through an integrated application of control theory, operations research, and agent-based modeling.

3.4.2. Business frameworks and processes to support operational networks

A review of the literature on business frameworks and processes to support management of operational networks highlighted the following common points: supporting operational level networks, supporting processes involving several decision support modules and functions, and supporting networked manufacturing life cycle.

(Azevedo and Sousa, 2000) presented an order promising system that was intended to be used as part of a broader Decision Support System for production and operations planning of a distributed enterprise. (Van Assen, Hans and Van de velde, 2000) developed an agile planning and control framework for customer order driven discrete parts manufacturing environments. There are three major components of this framework: a central planning and control system; a decentralized planning and control system for each manufacturing stage; and an information management system. (Manthou, Vlachopoulou and Folinas, 2004) developed an e-supply chain partners relationship management module for companies to quickly build or break down relationships with the customers. The module also supports the assessment of the channel performances in order to increase profitability and customer satisfaction. An information system for agile interactions between companies and customers in a mass customization environment is presented by (Frutos and Borenstein, 2004). This system combines internet-based technology and object object-oriented programming in order to provide smart tools for rapid and responsive customer interaction.

(Piramuthu, 2005) developed a knowledge based framework to hierarchically configure a dynamic supply chain by associating the best node, at each stage of the network. A framework for designing agile and interoperable VEs is proposed by (Kim *et al.*, 2006). This framework combines enterprise architecture, a model driven architecture, a domain specific methodology, and meta-modeling and framework based development approaches. An agent based model of supply chains operating in a mass customization context was developed by (Labarthe *et al.*, 2007) and applied to a case study in the golf club sector.

(Thimm and Rasmussen, 2010) developed a system for collaborative networks that was composed of by a DSS and a transparency support service. The DSS supports VE creation by exploring and evaluating potential candidates; while the transparency support service promotes and supports security within the network. Maintaining transparency of information is a good approach to cultivate trust through the network. (Shafiei, Sundaram and Piramuthu, 2012) developed and proposed a multi enterprise system for supporting SCM collaboration decision making processes. (Chen and Li, 2013) have proposed an integration framework, for production planning and control, and provided an application of the information technology in networked manufacturing. A rapid response production system was proposed by (Shan *et al.*, 2013) that was later implemented in an aircraft manufacturing company. The system is activated when an abnormal event occurs. An information system to support project management within an extended enterprise was developed by (Braglia and Frosolini, 2013) and tested in the inter-organizational processes characterizing the luxury shipbuilding industry. The observed benefits include reduction of errors, time savings, and enhancement in planning and execution of projects.

3.4.3. Some observations

Through our literature review, we have not come across any study that relates the company’s business strategy with operational level ICT initiatives. Some of the reviewed papers work on the integration of the operational level, with no evidence of strategy concerns or follow an incremental approach, where they initially develop a business architecture and then create more focused decision support tools. Our main observation is that, while the theoretical literature continuously repeats the need for strategic and operational alignment and for business strategy and ICT strategy alignment, in practice and in general, applications are very limited and deceiving.

On the other hand, the literature on Collaborative Networks mainly covers research to guide real life applications and focuses on developing practical tools to support inter organizational collaboration. Organizations are looking for methodologies to support a high level of integration and due to the fact that collaboration brings many immediate benefits to all partners, the development of a long term vision and of a strategy was been ignored.

3.5. ICT Tools

Based on the ICT requirements and literature review findings, we have developed a set of ICT tools to assist SME network functions and the DMN life cycle. Initially, a conceptual framework that frames SME network functions is described along with its components and explanations. The developed framework covers three main functions: SME network support functions, e-commerce functions and DMN support functions.

3.5.1. Illustrative Example

In order to briefly present our business model, we have created a scenario where 12 partners form an SME for creating short term opportunistic networks (Dynamic Manufacturing Networks). In this example partner companies are denoted with N and operations are denoted with O.

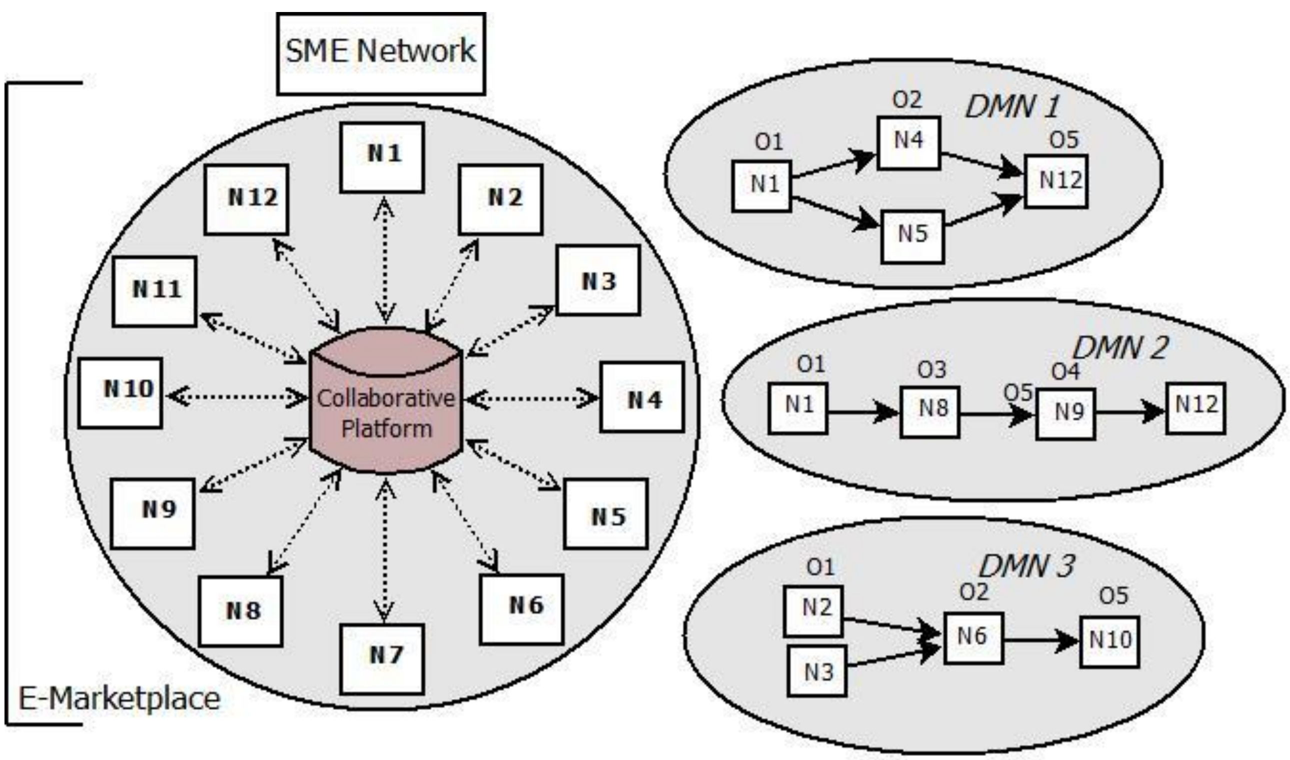

Figure 14 Business model organizational layers

As represented in Figure 14, 12 companies operating in the same industry, formed an alliance under the name SME network. These companies are all linked to and orchestrated by a Collaborative Platform, and they have different capabilities, capacities and geographical locations. The goal of the business model is to support the formation of short term DMNs to fulfill distinct business opportunities. Figure 14 denotes three different DMNs formed under the SME Network. The DMN is specifically designed in accordance to the production requirements and processes of each order.

In this scenario, production stages of each order can be represented with serial consecutive operations. As seen in Figure 15, these 12 partners operate in 5 successive production stages namely: N1,N2 and N3 in O1; N4, N5 and N6 in O2; N7 and N8 in O3; N9 in O4 and N10, N11 and N12 in O5. Since Operation 1 is the raw material echelon and Operation 5 is the customer delivery; these two operations are common in production processes of all orders.

Note that, while O1 can be performed by partners N1, N2 and N3, O4 can only be performed by N9. This may mean that, in some circumstances, O4 can be a bottleneck and that it might be interesting to associate another network partner to its operations.

The Collaborative Platform is linked to all SME Network partners and extracts real time information from their ICT bases. While the SME Network is a long term network, DMNs are temporary. Every time a new business opportunity arises or a new order is received, the DMN life cycle module of the collaborative platform is triggered in order to create a DMN. A list of possible DMN configurations will be generated considering different objectives, and a final DMN configuration will be selected among the available options. Each DMN will be monitored during its operations and intervened in case of disruptions or crisis. At the end of the DMN life cycle its performance will be measured in different dimensions and the measured values will be stored in the SME Network data base.

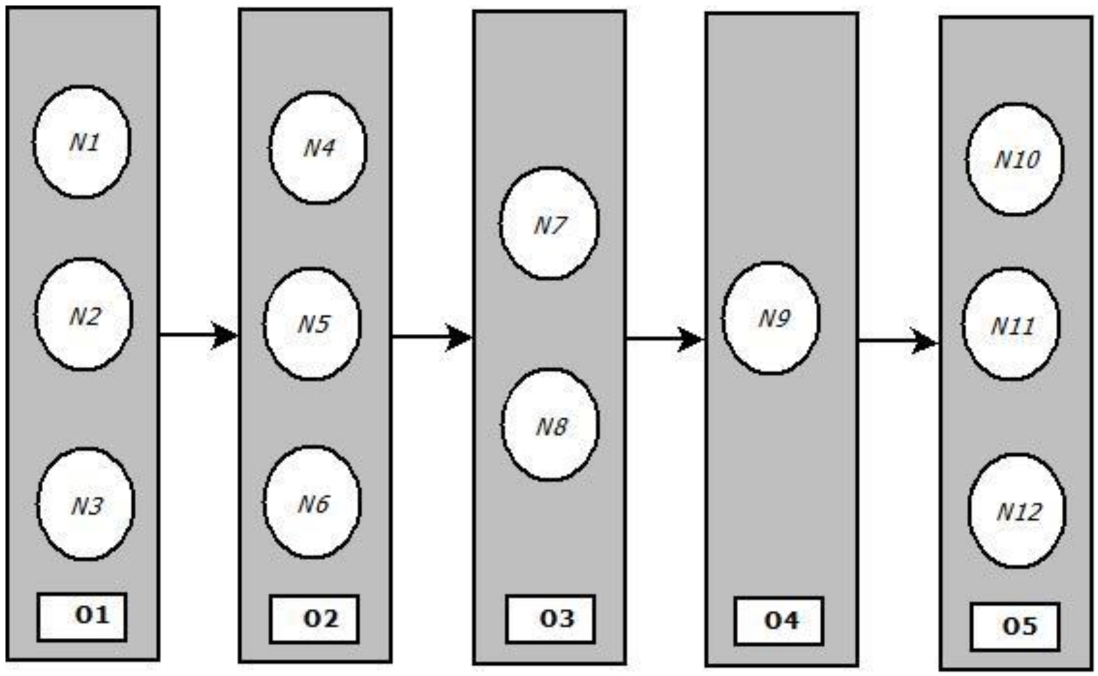

Figure 15 Industry network structure

The DMN network structure will be determined in accordance with order characteristics. While some orders require being processed through all operations, some operations might be unnecessary in other orders. Moreover, the DMN configurations will obviously also depend on the characteristics of orders and partners.

3.5.2. Business Model Conceptual Framework

The proposed framework is composed by three modules, associated to the focus and planning range of the processes involved. The outputs of the Balanced Scorecards (from the previous section) have been grouped in order to create this framework (see Figure 16).

Figure 16 Conceptual framework of the business model

3.5.2.1. SME Network Support Functions

These functions enable long term planning of the SME network and assist its processes.

- **Group Cohesion Management:** This function involves supervision of the soft factors that are important, in the long run, to enable harmony among network members. It is responsible for collecting quantitative measures for each group cohesion factor, tracking those measures through the network time line, and taking the necessary actions when a critical level is reached. The following submodules exist within this module: Trust Management; Reliability Management; and Fairness Management.
- **IS & ICT Development:** Here, one of the most basic tasks of Information System (IS) design is standardizing and integrating the heterogeneous information Systems of network members, under a common framework (Coronado M, Sarhadi and Millar, 2002). This specific function will be used to build and manage the ICT platform of the SME Network.
- **Membership Management:** This function involves keeping and tracking partner profiles, supporting network association and dissociation decisions and searching for new partners. Partner association and dissociation decisions will be taken based on the potential contribution and past performance of each partner.
- **Strategic Planning:** This function is responsible for setting and tracking long term goals, and for aligning operations with strategy.
- **Collaborative Decision Making:** Collaborative networks are particularly challenged in terms of decision making, due to the diverse and autonomous nature of their stakeholders. Group decision making processes need to be supported via online modules to enable communication, along with strong decision support tools to provide solid guidance.

- **Performance Management:** This function is used for keeping track of individual and network-wide performances. Financial (e.g. rate of return on investment, sales revenue, profit, increase in market share, etc.) and non-financial (time to develop new products, time to reach a new market, manufacturing cycle time, time to complete the partnership formation process, etc.) metrics should be developed in order to measure network and partner performances.

- **Collaborative Product Development:** One of the most important benefits of SME networks is the synergy they provide through collaborative product development. By sharing ideas and joining individual SME competencies in flexibility and customization, the network can bring new products and patents to the industry. This process later can lead an SME network to create strong brands and increase its market share.

- **Reporting:** Network partners share real time data on their capabilities, costs, capacities, future schedules, etc. In order to convince the partners to share these private data in real time, trust needs to be built among network partners. Reporting the network actions and sharing information on the Network and the partners are ways to increase trust and transparency.

- **Finance:** This function covers a wide range of operations such as financial evaluation and consultancy, tax administration, stock market operations, protection of assets, investor relations, short term financing, investment, insurance, and financial statements preparation.

3.5.2.2. E-Commerce Functions

The E-commerce module enables integration of dispersed customers and as an agile manufacturing enabler that supports online transactions and assists all processes behind trading, from sourcing to after sales support. In our framework this module provides the following functions:

- **Opportunity Search:** DMNs are opportunistic networks that are formed to satisfy specific business opportunities. These opportunities vary from fulfilling a one-time customer order to manufacturing of a product line. It is the duty of this function to search and reach new business opportunities, contact with potential customers and expand the business to potential market niches.

- **Order Promising:** This function involves the following processes: Order Acceptance; Order Prioritization; and Order Classification. If the network capacity is less than the capacity required to process all orders, it is necessary to select and accept part of the orders, and to reject or to delay others. In order to select more valuable orders, order classification tools can be employed. These tools will calculate the priorities of all received orders, classify them according to their values and give the order acceptance/ rejection/ postponement decisions accordingly.
- **E-Marketplace:** This is a customer interface embodying a catalog of products previously manufactured by the network. In the beginning of an order submission process, the customer needs to define the product configuration and specify the requested due date, delivery location and order volume.
- **Brand Management:** Managing the creation and development of brands through advertising and marketing strategies can be an important function of the system. Brand development generates customer loyalty, higher profit margins and financial strength (that will increase the survival chance of the network and its members, in economic crisis).
- **Pricing:** Pricing strategies might be implemented in order to create future demand, decrease demand uncertainty and increase customer loyalty. Possible strategies are quantity discounts, promotion incentives, etc.
- **Customer Relations:** This function handles customer communication, and customer and order data analysis, to better understand preference patterns. Here possible tools are customer prioritization, customer segmentation, and customer tracking. Through these tools the SME network can forecast customer preferences, develop customized products, make better customer selection, and invest in more valuable customers.

- **After Sales Support:** After sales support function and team will provide online support to customers in dealing with possible problems that are related with quantity, quality, product delivery, logistics and product characteristics.

3.5.2.3. DMN Support functions

As the short term operational activity of the SME network, a DMN requires specific DSSs for different phases of its life cycle. The DMN life cycle phases are creation; operation; tracking; crisis Management; and dissolution. To answer this need, the following functions were designed to help configure DMNs and to track and control their operations:

- **DMN Creation:** The DMN Creation module is responsible for extracting partner related data from the Collaborative Platform and using the decision support tools and models, to form the DMN. This module covers both DMN formation and DMN operational planning decision making. These decisions can either be supported by an integrated planning tool combining the two problems, or they can be solved in sequence. While the DMN formation covers the assignment of production processes to different partners, operational planning covers detailed planning, including scheduling and lot sizing decisions. One of the most important concerns in DMN formation is the criteria used in decision making.
- **DMN Tracking:** An important concern in DMN management is figuring out ways to deal with uncertainties arising from partners' autonomous and dispersed nature. An order tracking function should monitor each order through their execution, and be responsible for triggering an event management module, if a disruption occurs. The DMN tracking function covers partner tracking and logistics tracking.
- **DMN Performance Assessment:** The DMN performance assessment function focuses on measuring partner performances, through the DMN life cycle. These performance indicators may include measures and aspects such as: on time delivery ratio; quality performance; the willingness to take initiative in terms of crisis; etc. The assessment results can further be used for Cost and Benefit sharing decision making. Moreover, the results will be stored in the database, in order to track the long term performances of partners and of the network.

- **DMN Sharing Mechanisms:** These mechanisms are used for benefit and cost sharing. While a part of the profit is saved by the SME network, an important part of the DMN profit will be shared by the DMN partners. Performance assessment results are used for this purpose.
- **DMN Crisis Management:** The DMN Risk Management and DMN Event Management modules are the components of the DMN crisis management function. Risk Management is used to forecast future deviations, based on past partner performances and potential process risks, DMN Event Management module anticipates necessary actions in case an unwanted event occurs.

3.5.3. Functional, Informational and Process Flow of the Business Model

We propose here an organization of the functional flows as follows: Order Promising; DMN Life Cycle Management; Customer Relations; Membership Management; and Group Cohesion Management. Figure 17 shows the functional flows of the ICT system. Figure 18 presents the process flows of the system, and Table 10 presents the informational flows between modules.

The overall process of operational planning in an SME network starts with a customer interaction through the e-marketplace. The production system operates under an Available to Process (ATP) strategy. Once the e-marketplace receives a new customer order, the order promising module will be triggered, in order to check order feasibility both in terms of available capacity and required competencies. Online partner and order information will be extracted via the DMN Collaborative Platform. After the Order Acceptance submodule confirms acceptance of an order, this order will be joined with other orders for classification and prioritization. The Order Prioritization submodule will compute order priorities, via a multi-criteria decision making tool. Order priorities will be utilized in the DMN Creation submodule, so that more beneficial orders are processed first. On the other hand, the Order Classification submodule will compute order classes through data mining approaches. Order classes can be used in strategy and promotion development for different order classes. These modules will be fed with information on order characteristics (due date, volume, processing time, etc.) and on customer characteristics.

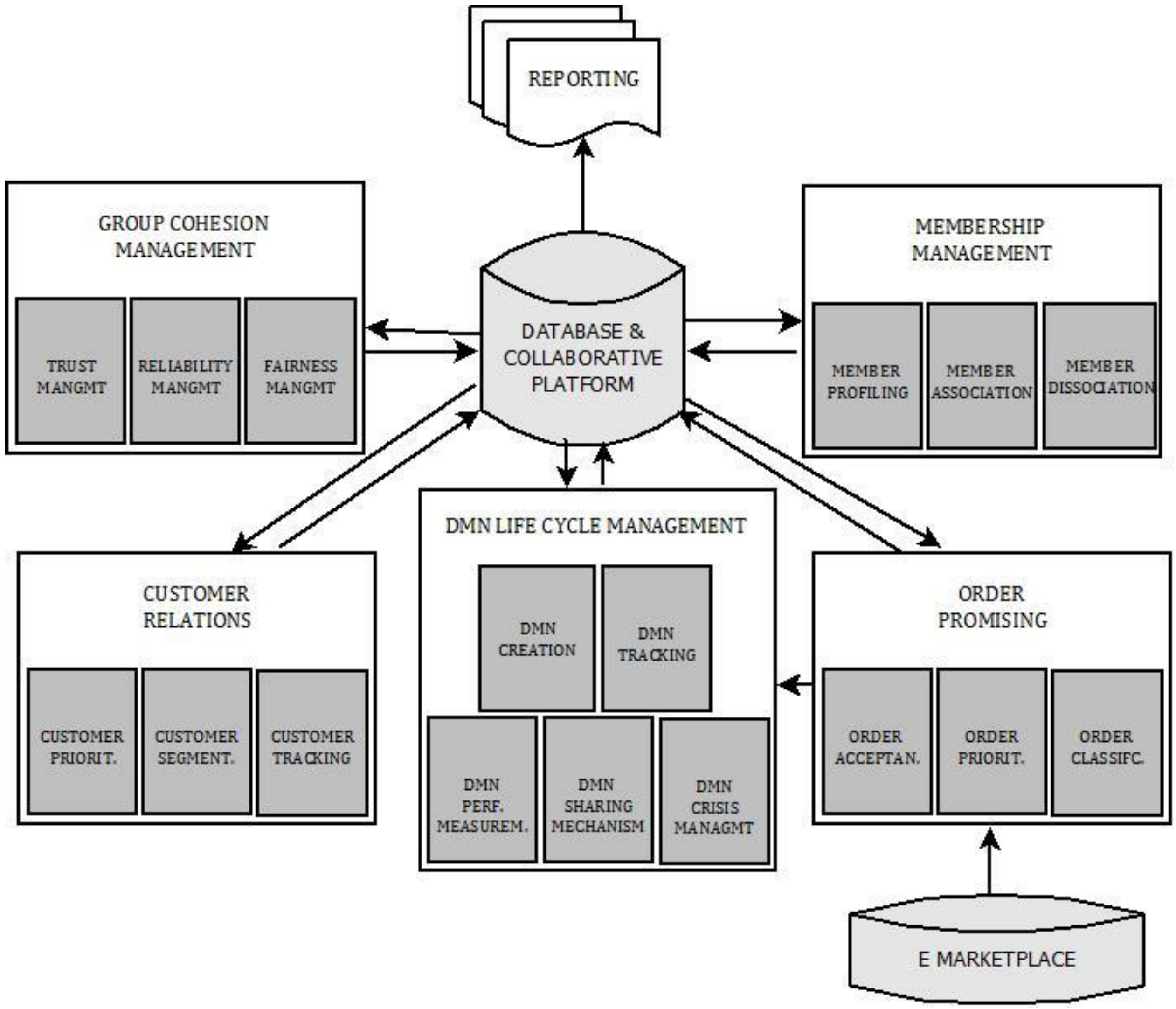

Figure 17 Functional flows

In the DMN Creation submodule of DMN Life Cycle Management module, a multi-objective mathematical model will be employed to decide DMN configuration and to compute the production and transportation lot sizes. The model will use several objectives such as cost, flexibility, partner reliability, order priority or operational risk and will take into account partner capacities, capabilities, order priorities, and costs. The order priorities generated by the Order Prioritization submodule and customer priorities calculated by the Customer Prioritization submodule, will also be considered in the DMN formation process. Since DMNs typically serve to a group of distinct customers, it is a good strategy to take into account customer characteristics during DMN formation. In order to enable the formation of customer and order driven DMNs, the Customer Relations module will provide its input on customer priorities and customer segments. At this stage, the DMN Risk Management submodule of DMN Crisis Management uses mathematical tools to predict operational risks related to DMN processes, and integrates the results to the DMN creation process. Once the DMN configuration and operational plans are set, job orders will electronically be transmitted to selected partners. In order to maintain visibility within the network, all the partners of the SME network will receive a report stating the DMN configuration and plans.

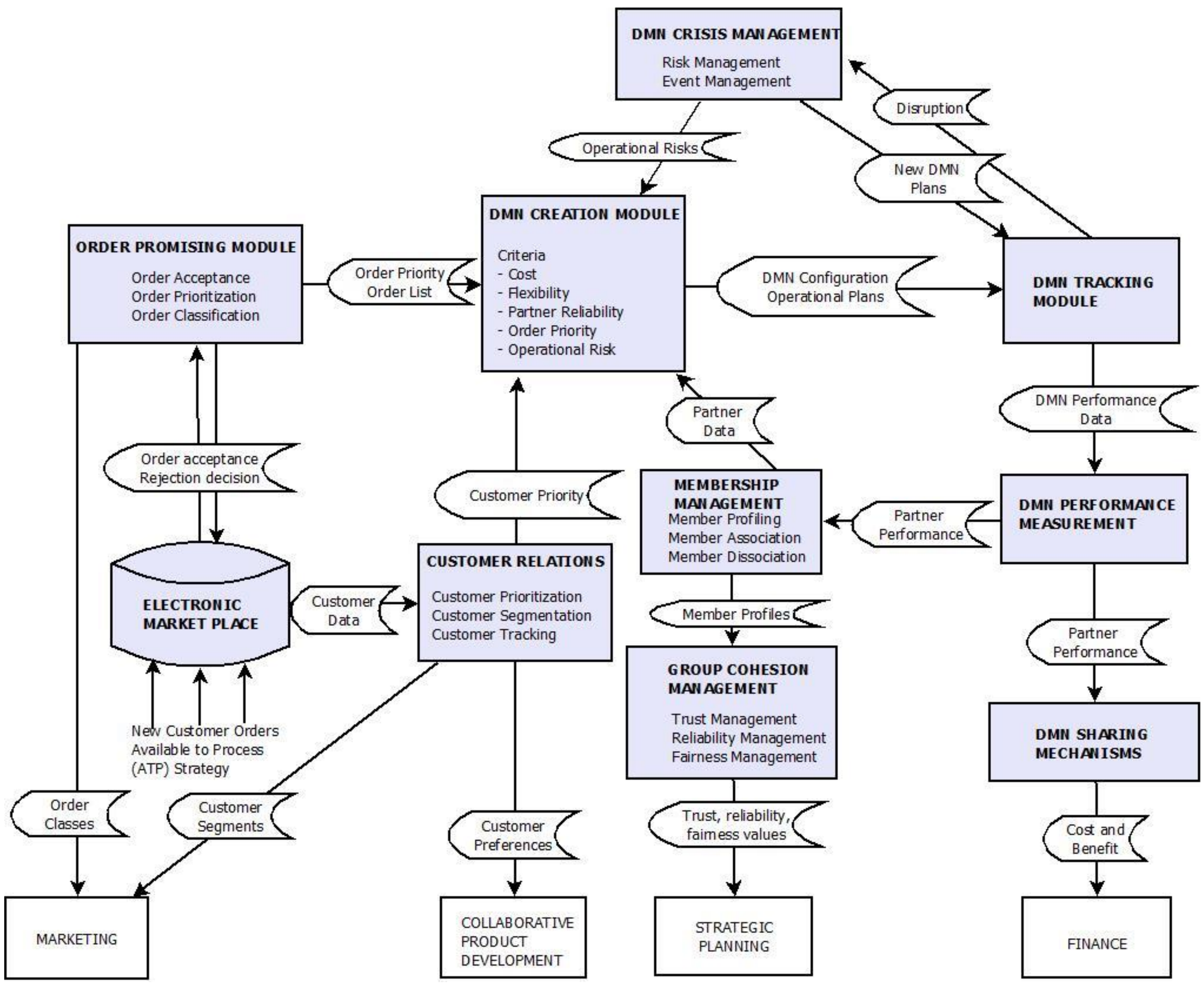

Figure 18 Process flows

In the DMN tracking phase, if a deviation from the initial plan is detected, the DMN Event Management submodule of the DMN Crisis Management submodule will trigger an action. It may either reschedule production among current DMN partners, or include new partners to the DMN in order to assign them the failed operations. Once the operations are done, the DMN Performance Measurement submodule assesses the performance of each partner. Moreover DMN partners will also evaluate their trust towards the SME network and the other partners. DMN performance assessments will be stored in the Collaborative Platform database for future tracking purposes. While failing in one DMN is probably acceptable for a partner, failing frequently is a big problem that has to be taken care of. Finally the DMN Sharing module will employ decision making mechanisms to partition joint costs and benefits among partners, by taking into account their performances within the DMN.

The Customer Relations module analyzes customer data, and consists of three distinct submodules: Customer Prioritization; Customer Segmentation; and Customer Tracking. Initially, the Customer Prioritization submodule feeds the DMN Creation submodule with values for customer priorities. The Customer Segmentation submodule then creates customer segments, again based on past customer information, thus providing information that can be utilized to develop strategies and promotions for similar customers. On the other hand, the Customer Tracking submodule calculates customer preference patterns, in order to support product development.

Table 10 Informational Flow between Modules and their explanation

Starting Module	Information	Received Module	Purpose
Order Acceptance	Accepted order list	DMN Creation	To initiate DMN formation
Order Prioritization	Order priorities	DMN Creation	To serve better to more prioritized orders
Order Classification	Order classes	Marketing	To define marketing strategies and service standards for different order classes
DMN Creation	DMN configuration	DMN Tracking	To monitor DMN operations
DMN Performance Measurement	DMN Performance	Membership Management DMN Sharing Mechanisms	To update performance measures in member profiling If member profiles get below threshold, dissociation may occur. To enable cost and benefit sharing in accordance with partner performances.
DMN Sharing Mechanisms	Shared Cost and Benefits for each partner	Finance	To distribute joint benefits and costs among the network partners.

DMN Risk Management	DMN Operational Risks	DMN Creation	To integrate operational risks into DMN creation allows the formation of a more reliable network and processes
DMN Event Management	Configuration and Operational Plans of new DMNs formed after tracking of a disruption	DMN Tracking	To deal with deviations from the initial plan
DMN Tracking	DMN Disruption Data	DMN Event Management DMN Performance Measurement	To inform Event Management about disruptions To assess actual performance of DMN partners compared to expected
Customer Prioritization	Customer Priorities	DMN Creation	Customer priorities are taken as a dimension in DMN Creation to form customer driven DMNs.
Customer Segmentation	Customer Segments	Marketing	Customer segments help promotion and strategy development for customers
Customer Tracking	Customer preferences and patterns	Collaborative Product Development	To be used as input to feed Collaborative Product Development.
Member Profiling	Partner Capabilities Partner Performances	DMN Creation Member Dissociation	Member profiling will transfer partner capability data to the DMN creation module. Moreover the system notifies the SME Network to take action (warning/dissociation) when a partner shows low performance
Member Association	New Member Data	Member profiling	To measure future benefits of a potential partner to the SME Network. If the partner is accepted; Member Profiling submodule will capture and store partner capability data
Member Dissociation	Member dissociation decision	Member Profiling	Once a partner is dissociated from the SME network, a predesigned process will be followed. Member information will be extracted from member profiling
Trust Management	Trust values	Strategic Planning	To track and control trust level within the SME Network If trust values are below a threshold, the SME network may develop strategies to deal with the challenge. Improving visibility by reporting and increasing communication through group meetings and creating polls are possible tools to increase trust.

Reliability Management	Reliability values	Strategic Planning	To calculate, track and control reliability within the SME network. Strategies such as offering incentives to increase reliability of the partners can be considered as a part of Strategic Planning
Fairness Management	Fairness Values	Strategic Planning	To track and control the SME Network members perception of fairness within the network Taking periodical partner feedback on their perception of fairness and develop strategies to improve the measure.

Management of DMN soft factors, (trust, reliability and fairness) are the tasks associated with Group Cohesion Management. This module is responsible for computing group cohesion measures, keeping track of these measures and taking actions to maintain group harmony. While reliability is a measurable indicator of group cohesion; fairness and trust depend on the perception of the SME network members. In the Reliability Management submodule, the reliability values calculated by the Performance Measurement submodule are tracked and controlled. If the reliability of a partner falls behind a predefined threshold, the Membership Management module either warns the partner, or decides its dissociation from the SME network. In order to measure trust and fairness; surveys, polls, and group interviews will be performed. The lack of trust and fairness within the network is a great threat to network sustainability, and, therefore, in case the measures fall below a threshold, Membership Management should consider developing strategies to deal with that problem.

Membership Management includes the following submodules: Member Profiling; Member Association; and Member Dissociation submodules. Member profiling stores and updates data on member capabilities and performances. If a partner's performance and capabilities go beyond a threshold, member dissociation submodule will compute the future "value" of that partner and give a recommendation on what to do. The partner will be either given a warning to improve its performance, or will be informed about dissociation. On the other hand, when a new SME is considered to be involved as a partner, the Member Association submodule will compute its future contribution to the network, and provide a recommendation on what to do.

The database and collaborative platform are responsible for storage, and transfer of data and information between different modules. They work as interfaces, guaranteeing the quality of the functional flows.

3.6. Conclusions

In this work, we have developed a set of ICT Tools for a business model based on two organizational layers: SME Networks and Dynamic Manufacturing Networks. Initially, we have identified three components of the SME network vision: Sustainability; Survival; and Growth. Later, we have implemented a Balanced Scorecard approach to translate the SME network vision into operational level ICT initiatives. These ICT initiatives, along with comprehensive literature review findings, provided a basis to develop ICT tools for the SME Network and DMN business model.

Two layers of ICT Tools were developed for the business model: a conceptual framework to support SME Network functions; and functional, process and informational flows for the business model. These instruments are expected to adequately guide the development of focused decision support tools.

Nowadays, Collaborative Networks are highly dependent on ICT tools and automated processes. Developing such integrated tools by following a well-defined methodology will have several benefits. Since partners get involved in these collaborative networks mostly for long term benefits, developing a long term vision and aligning strategy with action improves the credibility of the Collaborative Network in the partners' perspective. Moreover, it broadens the short term oriented, financial benefits-focused perspective into longer term objectives, such as growth, sustainability and survival. Developing a clear vision and implementing it into operations increases the resilience of organizations in today's turbulent markets. And automated processes significantly shorten the decision making time and make the operational execution much easier.

Chapter 4: A Multi Objective Model For Dynamic Manufacturing Network Planning

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A Dynamic Manufacturing Network (DMN) is an application of the Virtual Enterprise (VE) business model to manufacturing that encompasses the planning needs of both integrated supply chains and VEs. DMNs are order driven networks that take wide advantages of ICT technology and automated processes. DMN design and planning is commonly made according to cost concerns, even though order and customer characteristics are the primary drivers of the network structure. In this chapter, we have focused on tackling this widely neglected research opportunity, by integrating order and customer characteristics into DMN formation and planning.

For this purpose, we have followed a three stage methodology. Initially, using the TOPSIS multi criteria decision making technique, we have calculated Order Criticality, Customer Priority and Manufacturer Reliability indexes. Later, we have provided a fuzzy inference system (FIS) to transform Order Criticality and Customer Priority into an Order Priority Index. Finally, we have combined Order Priority and Manufacturing Reliability in a multi objective model, together with cost minimization. The developed multi objective model allows generating solutions with a reasonable cost but that also assign reliable manufacturers to prioritized orders.

4.1. INTRODUCTION

With increasing competition occurring in between networks, rather than autonomous companies; manufacturers are looking for new innovative business strategies that can best support their industrial competencies and positioning. Agile manufacturing, relying on the philosophy of "rapidly reacting to change by adapting network configuration" stands out as one of the most utilized manufacturing strategies in this era (Pan and Nagi, 2010). Within agile manufacturing tools, we have approaches such as the Virtual Enterprise (VE), strategic partnership, rapid prototyping, e-commerce, and information sharing technologies (Gunasekaran, 1998). Dynamic Manufacturing Network, as a discrete manufacturing industry application of the VE business model, is also an extension of the more general agile manufacturing strategy.

Since discrete complex manufacturing industries require a high level of integration and agility, DMNs emerged with characteristics such as automated business processes, real time information sharing, and common ICT platforms. Generally, Dynamic Manufacturing Networks are based on an existing strategic partnership, dealing with supporting collaboration and providing ICT development. Once the strategic partnership is formed and information sharing and ICT tools are developed, DMNs can function as the operational unit of the partnership. In order to enable DMN formation and proper operation, members need to share data on their available capacities, inventories, lead times, production schedules and cost structure (Viswanadham and Gaonkar, 2003). The ICT enabled platform is responsible for assisting each DMN through their lifecycle (formation, operation, monitoring and dissolution) and for providing tools for DMN functions supporting performance management and evaluation, trust management, order promising, etc. One of the main tasks related to a strategic partnership is to collect and store the data generated by each DMN through its life cycle. There are three main dimensions of stored DMN related data, namely: data on customer characteristics; data on manufacturer performance; and data on order characteristics. In order to take full advantage of a DMN ICT platform, it is important to analyze this stored data and learn from it, by integrating the retrieved information into operational processes as a feedback.

A DMN is an order driven network that can be viewed as an intermediary between manufacturers and customers. (Viswanadham and Gaonkar, 2003) state that the optimal DMN configuration can be completely different from one customer order to another one. The location of the customer, the time required to manufacture the order, the order lot size and the order due date are the main parameters that affect the network configuration and operational planning decisions.

Even though the demand structure is the main driver behind the design of agile and dynamic manufacturing networks, current studies focus on cost minimization and profit maximization (Viswanadham and Gaonkar, 2003; Babazadeh, Razmi and Ghodsi, 2012). This is in fact a weak representation of reality since DMNs are collaborative networks that need to take into account the status of their stakeholders and the social considerations in their planning processes.

An order driven network responds to customers by planning production processes after order confirmation. DMNs cannot hold safety stock or inventory, since they receive customized orders from various customers, and it is impossible to foresee the demand. Therefore, in order to quickly respond to customer orders, strategic partnership needs to quickly communicate with its members and form DMNs in order to fulfill each order. The customer satisfaction achieved in a DMN depends on delivering the order to the customer, on time, with the right characteristics, with adequate quality, and in the agreed quantity. However, DMN members have autonomous structures and providing complete control over internal operations of DMN members is impossible. A possible delay in the operations of one partner may trigger a chain reaction in the overall production processes and lead to a delay in delivery time. Delayed or failed deliveries jeopardize the overall SME network reputation and decrease its reliability. Therefore, developing quantitative measures for partner and network performances will create a positive control mechanism over DMN actions.

The DMN formation and operational planning processes are expected to assign a set of customer orders with different characteristics to a set of manufacturing partners. The stored data on orders, customers and partners can be utilized in supporting future DMN formation and operational planning decisions. Even though ICT is widely used in DMNs and decision support tools are available, the order driven nature of DMNs is often neglected in network formation and operational planning. Orders and partners are taken in a similar way, while in reality some customers are more prioritized than others, some partners are more reliable than others, and some orders are more critical than others.

In this research, we have focused on integrating customer, manufacturer and order characteristics into DMN formation and operational planning. We have therefore considered these characteristics in our mathematical models, along with cost minimization. A multi objective model is proposed, to minimize costs and maximize order priority and manufacturer reliability. In order to provide an order priority index, we have initially computed customer priority and order criticality indexes, by applying TOPSIS methodology. Moreover, a manufacturing reliability index was also computed through the TOPSIS methodology. Then, a fuzzy inference system that transforms the order criticality and the customer priority indexes into an order priority index was developed. Finally, we have combined the order priority and the manufacturing reliability indexes in a multi objective model, with cost minimization. The developed methodology can be used as a decision support system, where alternative solutions are simultaneously created, and decision makers are provided with a range of network configurations, for choosing according to their own preferences and priorities.

4.2. LITERATURE REVIEW: OPERATIONAL PLANNING IN NETWORKED MANUFACTURING

In manufacturing network formation and operational planning, cost minimization or profit maximization have always been the fundamental drivers. Existing models consider cost as the more relevant factor, while adding various parameters and concerns to make the model more realistic.

(Viswanadham and Gaonkar, 2003) proposed a MILP model for profit maximization in the formation and operational synchronization of a four-stage internet enabled DMN. (Chauhan *et al.*, 2006) made one of the earliest attempts to integrate network formation and operational planning decisions in an agile manufacturing context, and developed a path relaxation based heuristic to solve problems with larger instances in reasonable time. In a more recent paper, (Pan and Nagi, 2013) generalize the limiting assumption of single partner selection to multiple partners. (Huang and Yao, 2013) developed a time varying lot sizing model for a serial supply chain, with the objective of minimizing total set up and production costs. A three phase heuristic algorithm was proposed to solve the problem.

There is also a literature stream that considers uncertainty concerns in these decision making processes. A robust optimization model to minimize total operational costs, under different economic growth scenarios, was developed by (Leung *et al.*, 2007). (Pan and Nagi, 2010) built a robust optimization model, considering demand uncertainty, for short term supply chain formation. (Peidro *et al.*, 2009) proposed a fuzzy mathematical programming model for supply chain planning that considers supply, demand and process uncertainties. A strategic and tactical level network planning model, for global supply chains, to minimize annual capital and operational costs under uncertain demand was developed by (Georgiadis *et al.*, 2011).

Another interesting research stream takes into account the multi-objective and multi-criteria nature of networked manufacturing. (Chen and Lee, 2004) developed a Mixed Integer Non Linear Programming model that deals with uncertainty in market demand and product prices. The model considers several conflicting objectives in network formation, such as fair profit distribution among all members, safe inventory levels, maximum customer service level, and robustness of decisions for uncertain product demands. (Piramuthu, 2005) proposed a knowledge-based framework to hierarchically configure a dynamic supply chain. This framework selects the best node at each stage of the network, according to a combination of order attributes (price, lead time, quantity, etc.). (Dotoli, Fanti and Meloni, 2006) developed a model for partner selection and network configuration in Internet Enabled Supply Chains (IESC). The IESC network structure is represented by a digraph, with single and multi-objective optimization models, that support flexibility, agility and environmental performance in the design process. (Jarimo and Salo, 2009) proposed a multi-criteria MILP model for partner selection in VO formation. With cost minimization, the risk of capacity short fall, and inter-organizational dependencies based on the success of past collaboration were also considered. (Yao and Liu, 2009) proposed a multi-objective model supporting supply chain scheduling in mass customization, which maximizes profits and minimizes costs, while enabling on time delivery. (Papakostas *et al.*, 2012) proposed a four stage approach for DMN configuration and planning, that creates alternative configurations, simulates alternative samples, evaluates alternatives, and ranks DMN configurations according to identified criteria weights(average tardiness and cost). A three stage, multi item, bi-objective MILP model that minimizes cost and activity days was developed by (Zhang, Luo and Huang, 2012) for supply chain design of dispersed manufacturing in China, considering global manufacturing parameters such as currency exchange rate, production cost, transportation cost, and export VAT rate. (Papakostas *et al.*, 2014) addressed the DMN creation problem by defining a utility function with several criteria such as cost, duration and quality. The model is applied to a pool of potential partners in the furniture manufacturing industry.

In general, for simplification purposes, the models found in the literature do not consider different product structures and production process characteristics. However, in the demand driven network concept, ignoring scenarios with multiple orders or orders with different routings is a weak representation of the agile manufacturing strategy. New manufacturing planning models should be flexible enough to synchronously plan different products, especially now, when products have short life cycles and change rapidly.

We have also found out that many papers are considering operational planning as an isolated one time decision, and not taking advantage of long term stored data. Moreover, a single objective quantitative optimization model cannot capture the complex nature of DMNs since these are complex systems with many stakeholders, multiple customers, manufacturers and orders. There are also many soft factors that need to be taken into account. Along with costs, we also need to consider lead time and quality one can list culture, individual/group behavior, social relations, trust, reliability, and customer satisfaction etc. It is important to note that DMNs are both supply chains and VEs. Soft factors such as network wide trust or cultural and human barriers are also important factors in DMN planning, even though the DMN business model supports full integration and high level of information sharing between partners.

4.3. METHODOLOGY

In this section, we will present a three stage methodology we have designed to assist the process of generating operational plans for DMNs (See Figure 19). Initially we have computed an Order Criticality index, a Customer Priority index and a Manufacturer Reliability index using a TOPSIS approach, based on customer, order and manufacturer characteristics, drawn out of stored past data In the second step of the methodology, an Order Priority index is computed through the Customer Priority and the Order Criticality indexes, via a fuzzy inference system. Finally we have utilized a Multi-objective Mixed Integer Linear Programming (MILP) model, to produce balanced operational plans for both cost minimization and reliability maximization. Our objective in applying this methodology is not only selecting the network configuration with minimum cost but, also assigning more prioritized orders to more reliable manufacturers.

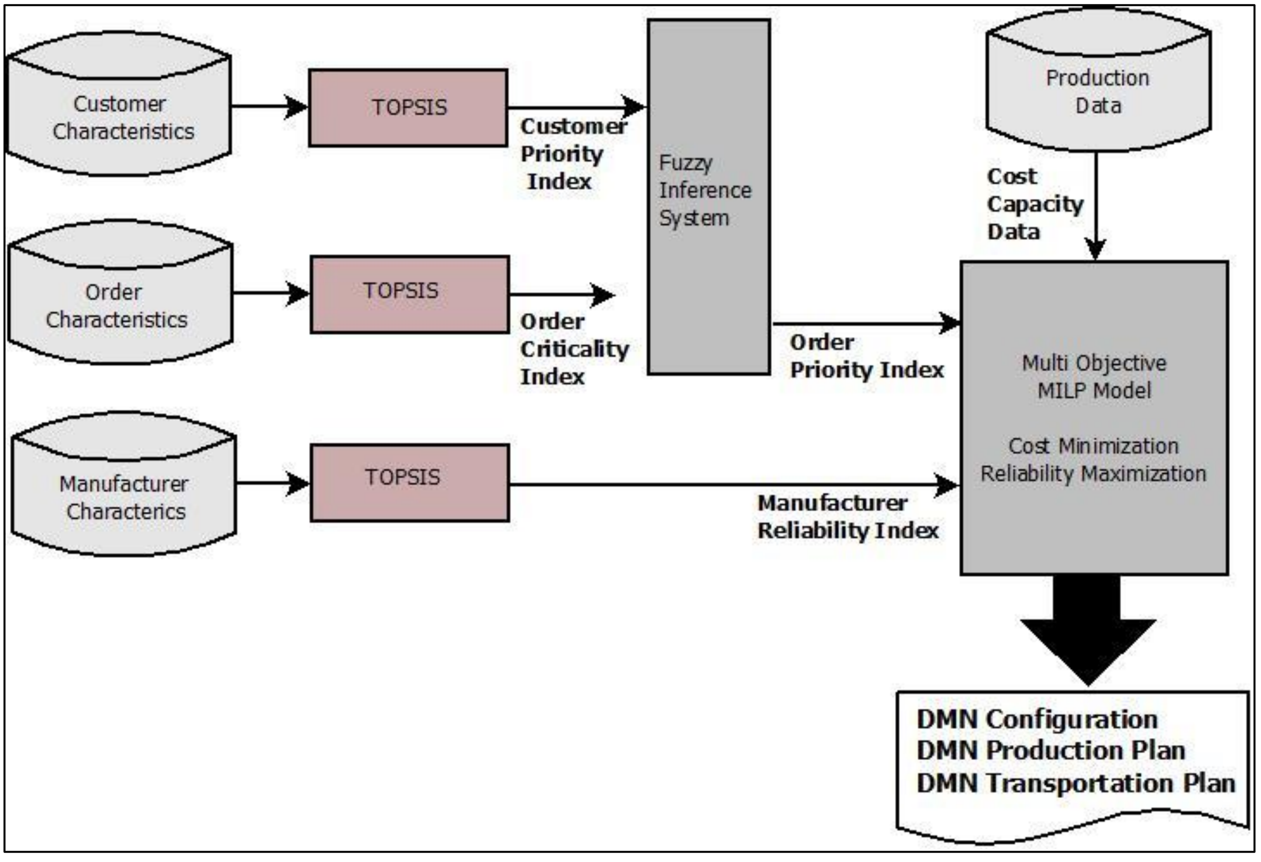

Figure 19 Methodology

4.3.1. TOPSIS

The SME network collaborative platform tracks and stores historical data on manufacturers, customers and orders. The stored multi-dimensional data requires some processing in order to be utilized in operational planning. We have employed the TOPSIS multi criteria decision making methodology in generating Customer Priority, Order Criticality and Manufacturer Reliability indexes. TOPSIS was selected as it is mathematically sound and easy to apply as a multi-criteria decision making technique. In the initial phase of the work, we aim to integrate different dimensions of each data category under the above three indexes.

TOPSIS ("Technique of Order Preference Similarity to the Ideal Solution") was introduced by Hwang and Yoon in 1981, and since then it has been extensively used as a multi criteria decision making technique. TOPSIS relies on the idea that the best solution to a decision making problem should be at the shortest distance to the ideal solution, and furthest distance from the negative ideal solution (Behzadian *et al.*, 2012). It is based on sound mathematical principles, and has a clear and easy application procedure. The only subjective parameters involved in TOPSIS are the weights associated with each criterion.

4.3.1.1. Algorithm

In TOPSIS, the initial step is to form a decision matrix consisting of all decision making alternatives and criteria. In a second phase, a normalized decision matrix will be created. Later, in step three, a weighted normalized decision matrix will be computed by multiplying each matrix element with their associated weights. Step four consists of determining negative and positive ideal solutions. Step five computes the distance of each alternative to the positive and negative ideal solutions. The Euclidian distance was selected for this purpose, since it is the most extensively used measure. In the final step of the process a relative closeness coefficient is computed, so that the set of alternatives can be ranked according to this coefficient.

Step 1: Create the decision matrix D as a combination of alternatives and criteria.

A_i $(1 \ldots i \ldots M) \Rightarrow$ M alternatives (rows)

C_j (1 … j … N) ⇒ N Criteria (columns)

$$D = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_M \end{matrix} \begin{matrix} C_1 & C_2 & \dots & C_N \\ \begin{bmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,N} \\ r_{2,1} & r_{2,2} & \cdots & r_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ r_{M,1} & r_{M,2} & \dots & r_{MN} \end{bmatrix} \end{matrix}$$

Step 2: Compute the normalized decision matrix

In order to compare different decision matrix elements, each element of the decision matrix D will be subject to normalization. Among various normalization techniques we have considered the distributive normalization technique:

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{M} r_{ij}^2}} \; \forall \; i = 1, \cdots, M \; and \;\; j = 1, \cdots N.$$

Step 3: Compute the weighted normalized decision matrix

In this step, each normalized score n_{ij} will be multiplied by the associated criterion weight w_j in order to compute the weighted score v_{ij}.

$$v_{ij} = w_j \times n_{ij}$$

Step 4: Determine the positive ideal and negative ideal solutions

This step consists of determining the positive and negative ideal solutions. The best performance on each criterion of the normalized decision matrix is considered as the ideal solution, while the worst performance is considered as the negative ideal solution.

Let A^+ be the set of positive ideal solutions, and A^- be the set of negative ideal solutions:

$$A^+ = (v_1^+, \cdots, v_N^+)$$
$$A^- = (v_1^-, \cdots, v_N^-)$$

where $v_j^+ = max_i(v_{ij})$ if the criterion i is to be maximized, and $v_j^+ = min_i(v_{ij})$ if criterion i is to be minimized; and $v_j^- = min(v_{ij})$ if the criterion i is to be maximized and $v_j^- = max_i(v_{ij})$ if criterion i is to be minimized.

Alternatively, an absolute ideal and anti-ideal point can be assigned by the decision maker, without analyzing the data.

<u>**Step 5:** Compute the distance from each solution to the ideal solution</u>

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \quad ,i = 1,2,\dots,M$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \quad ,i = 1,2,\dots,M$$

<u>**Step 6:** Compute the relative closeness to the ideal solution, rank the alternatives in descending order</u>

The values of "relative closeness" are used to rank the alternatives. The relative closeness of alternative A_i with respect to the positive ideal solution v^+ is given as:

$$\overline{C_\iota} = \frac{D_i^-}{D_i^+ + D_i^-}$$

The values of the closeness coefficient $\overline{C_\iota}$ lie in between 0 and 1. The preferable alternative is the one with the largest coefficient.

4.3.1.2. Criteria

In the design of DMNs, on time delivery of customer orders is a major concern, since partners are autonomous and independent, in planning and operating their internal processes. If one of the DMN members fails to follow their assigned DMN schedule and becomes late in their DMN related operations, a delay in customer delivery can be caused, and this may lead to the jeopardization of the whole SME network reputation. One of the main ways to overcome this problem is to assign manufacturing processes to reliable partners.

Table 11 covers the developed criteria used to compute the indexes (Customer Priority, Order Criticality and Manufacturer Reliability indexes).

Initially, it is important to measure how reliable each manufacturing partner is in order to have guidance on how to maximize reliability of each DMN. The reliability index of each manufacturer will be computed by using their past performances in several criteria. These criteria are identified as *on time delivery ratio, total contribution produced last year (in terms of volume produced), managerial assessment (over a scale of 1 to 100), average delays (caused in DMN related operations last year), ratio of rejected orders last year, ratio of orders delivered with adequate quality last year, frequency of selection to a DMN last year*.

On the other hand, when we focus on customer characteristics, considering that each customer has the same importance to the SME network is a weak representation of reality. In fact, some customers have more priority and potential than the rest of the customers. Prioritizing customers and standardizing services according to their importance seems to be a good strategy to deal with the challenges of current markets. The customer priority index can be measured by taking into account past customer performance and data. The criteria involved in the computation of index are: *average value of all orders, the order frequency per year, the collaboration time (in weeks), customer size (on a scale of 1-10), the average profit earned in the given orders (in percentage), on time payment ratio and average delay in payments (in weeks).*

The order characteristics are also considered in the model through several criteria: due date, total slack time, total number of operations involved in the manufacturing process, lot size (in terms of units) and financial value of the order. Even though the order priority is reflected in the scheduling, in general this priority is neglected in lot sizing.

Table 11 Indexes and Criteria

	Name of index	Measure	How to compute
Customer priority	Average value of all orders	Euros	Total value of all orders/Total number of orders received
	Order frequency per year	number	Number of orders received
	Collaboration time	weeks	Total weeks of serving to the customer
	Customer size	1 to 10	Assessment of customer size
	Average profit from given orders	%	Total profit/Total revenue*100
	On time payment	%	Number of orders paid on time/ Total number of orders*100
	Average delay in payments	weeks	Total delay in payments/Total number of orders received
Order criticality	Due date	weeks	Due date of the order starting from the present week
	Total slack time	weeks	Total time left to the due date -Total time required to process the order
	Total number of operations	number	Total number of echelons the order has to go through
	Lot size	number	Lot size of the order in terms of units
	Value	Euros	Total value of order
Manufacturer reliability	On time delivery	%	Number of orders delivered on time/Number of orders produced*100
	Total contribution last year	number	Total volume produced
	Managerial assessment	1 to 100	Assessment of manufacturer in terms of performance
	Average delays last year	weeks	Total delay in terms of weeks / Number of orders
	Rejected order last year	%	Number of rejected orders/ Number of assigned orders*100
	Adequate quality last year	%	Number of orders with adequate quality/Number of orders*100
	Frequency of selection to a DMN last year	number	Number of selections to a DMN

4.3.2. Fuzzy Inference System

After computing the three indexes, we have used a Fuzzy Inference System to translate the customer priority and the order criticality indexes into an order priority index. These indexes have values on an interval from 0 to 1. Based on fuzzy sets and a fuzzy rule system, the fuzzy output function f1 (p1, p2) is computed through a fuzzy inference system, and transformed into a crisp value via a centroid defuzzification system. We have used a Mamdani type fuzzy inference system as the most commonly used fuzzy inference system.

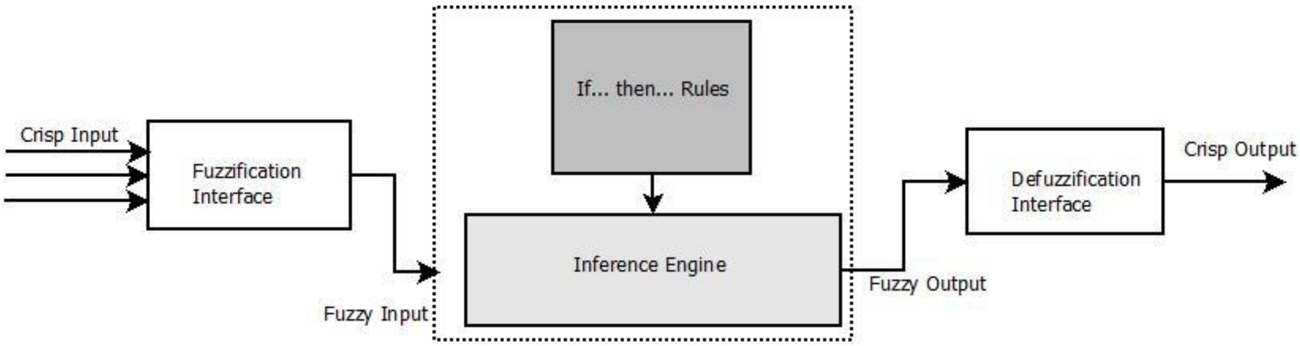

Figure 20 Fuzzy Inference System

As shown in Figure 20, a fuzzy inference system involves input and output parameters, fuzzy rules, fuzzy sets and defuzzification schemes.

Initially, input parameters (Order Criticality and Customer Priority) are fuzzified. Then, the fuzzy rule based system is applied in order to link fuzzy inputs to fuzzy outputs. Once the inputs are aggregated in a fuzzy form, defuzzification is employed. At this stage, the most commonly used method, (Centroid defuzzification) is utilized.

A fuzzy inference system is a simple way to include logical reasoning to inputs that are hard to relate with outputs. It is very difficult to come up with a mathematical formulation which relates the considered indexes. Through a fuzzy inference system it became possible to take expert ideas into account and use them to relate the indexes. We have utilized fuzzy rules developed by the Strategic Partnership (SME Network) members, by evaluating their preferences. With the help of the fuzzy inference system it is possible to include and reflect these preferences into the multi-objective model.

4.3.3. Multi Objective Model

We consider an order-driven network, where manufacturing is initiated by customer orders. The model is formulated with the assumption that manufacturing processes of production orders can be divided into serial production stages. For each production stage, there exist multiple candidate manufacturing units, with different cost structures. The Strategic Partnership deals with these concerns to enable DMN formation and operational planning.

The MILP model aims to assign the manufacturing stages (operations/echelons) of each order to manufacturing units, in this order driven, serial supply chain setting. This model is based on a network $G = (N, A)$, where the nodes (N) stand for candidate manufacturing units and the arcs (A) stand for connections/transportations between nodes that are performing consecutive operations.

Allowing planning of customer orders with different production routings is a *flexibility* and strength of the model. If we call the sequence of operations as O, and set of manufacturing units as N, for each customer order there is a subsequence of O $(O_k \subset O)$ that defines the manufacturing stages required to produce order k**.** Moreover, for every $i \in O$, there is a subset of N (denoted as $N_i \subset N$) that defines the subset of manufacturing units that are able to perform operation i. Production allocation and lot sizing decisions will be defined in a discrete time horizon, where a unit time period is denoted by t and where the last planning period is denoted by T.

We believe that a multi-order network, with various production routings, is a better representation of reality, since these networks are industry-wide and cover production of various different products. According to the model, production processes of each customer order can be planned by forming a serial network among a pool of manufacturing units. The model allows the selection of multiple manufacturing units for each operation.

Looking at the problem from a network point of view, we want to highlight that the set of manufacturing units also represents the set of nodes. The set of arcs A is composed of subsets A_k, each containing the set of arcs required to produce item k.

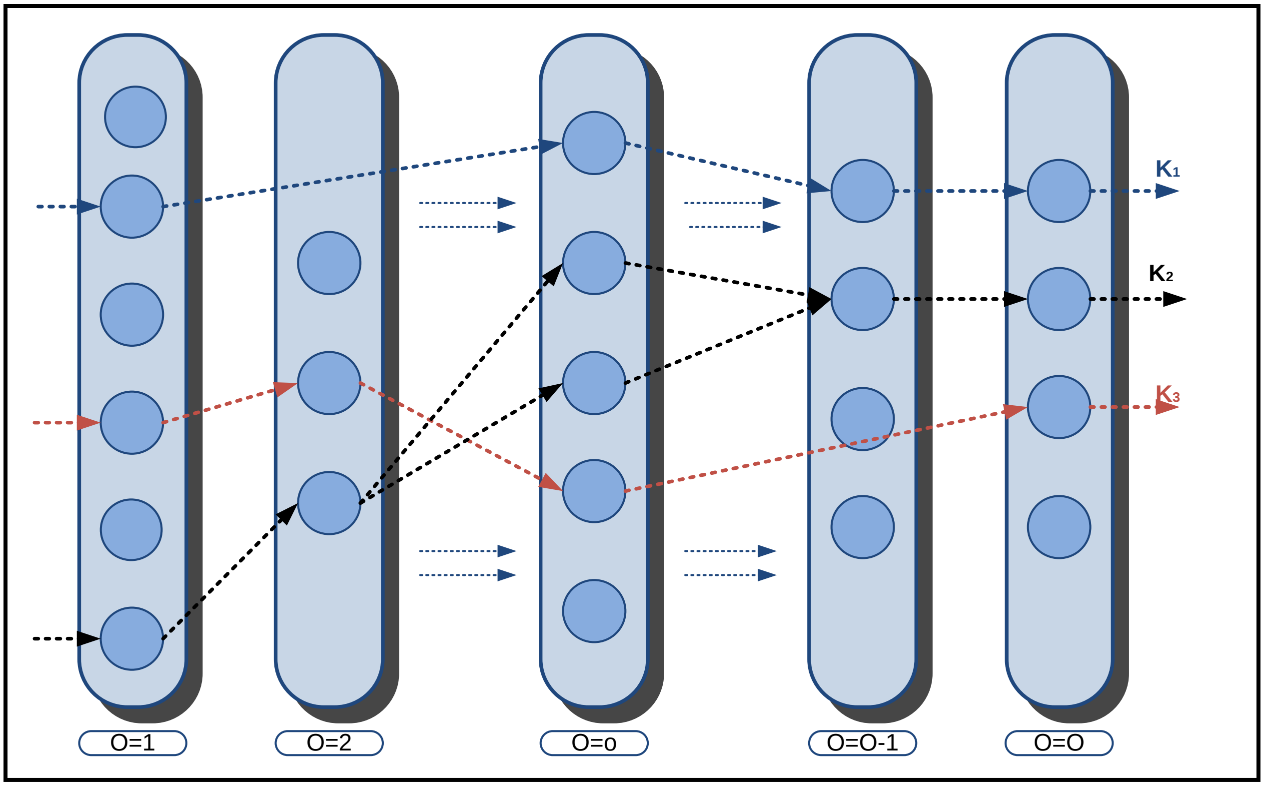

Figure 21 Representation of a multi -echelon, multi-order system

Figure 21 shows a network with 3 customer orders and 5 operations. Each order goes through different routes and there are different manufacturing units in each echelon to perform every operation. The first operation represents the set of raw material suppliers and the last operation stands for the set of shipping points. These two operations exist in the operational sequence of each customer order. Between these two operations, the proposed model allows flexible production steps for multi-echelon production processes.

In Table 12 we have listed the sets that are described above. Given deterministic demand, and costs for inventory holding, production, set up, transportation, node selection and assignment, the proposed multi objective model seeks a minimum-cost maximum order priority-driven reliability based network configuration and an operational plan that satisfies all constraints over the planning horizon.

Table 12 Sets from the model formulation

Set of operations in the manufacturing network	$O = \{1,2,\cdots,O\} \quad \forall\, i,j \in O$
Set of orders received for the planning horizon	$K = \{1,2,\dots,K\} \quad \forall\, k \in K$
Set of manufacturing units (nodes) in the manufacturing network	$N = \{1,2,\cdots,N\} \quad \forall\, n,m \in N$
Planning time horizon	$T = \{1,2,\cdots,T\} \quad \forall\, t \in T$
Set of customers	$C = \{1,2,\cdots,C\} \quad \forall\, c \in C$

4.3.3.1. Model assumptions

In order to model the DMN formation and operational planning problem, we have considered a generic supply chain with the following assumptions:

- the network manufactures customized orders of complex products, with low production volumes and high variety;
- different production orders are manufactured separately;
- each product has its own set up for each period;
- each customer order may have different unit processing times in different manufacturing units. (the reason for this difference is technology and labor structure differences between manufacturers);
- every manufacturing node shares its available capacity data for the planning horizon (available hours) (while there is a different set up cost assigned for each product for the sake of simplicity, set up times are ignored);
- all items have first and last operations in their operational routings (The first operation stands for raw material and the last operation stands for the customer shipping point);
- demand cannot be met before or after the order due date;

- there are both fixed and variable transportation costs involved (combining transportation of different orders between stages is allowed to enable economies of scale in transportation);
- each partner can only accept operation after being assigned a minimum volume of product;
- for the sake of simplicity, supplier capacity is considered infinite (an infinite amount of raw material is always assumed to be ready for production);
- orders are directly shipped from the last operation (customer shipping point) to customer locations;
- each order of each customer is processed separately, so that each order k can only be shipped to one customer c.

4.3.3.2. Parameters

$SC_{i,n}$: Cost of selecting node n, operation i, to the network

$AC_{k,i,n}$: Assignment cost of order k to operation i, node n

$FPC_{k,i,n}$: Fixed production cost of order k, at operation i, node n

$UPC_{,i,n}$: Processing cost of operation i, at node n, for one time unit

$UPT_{k,i,n}$: Unit processing time of order k, at operation i, node n

$CAP_{t,i,n}$:Total production capacity (total processing time) of node n, operation i, at time t

$FTC_{n,m}$: Fixed transportation cost, from node n to node m

$UTC_{n,m}$: Cost of transporting one kg of goods, from node n to node m

$HCS_{k,i,n}$: Pre-operation unit holding cost of order k, at operation i, node n

$HCF_{k,i,n}$: Post-operation unit holding cost of order, k at operation i, node n

$UW_{i,k}$: Weight of order k (kgs) at the end of operation i

$UW_{c,k}$: Weight of order k (kgs) at the last echelon, to be delivered to customer c

$TRCAP_{n,m}$: Transportation capacity, from node n to node m

$CDTRCAP_{c,n}$: Transportation capacity, from node n to customer c

$CDTRCost_{c,n}$: Transportation cost per kg of goods, from node n to customer c

T : Last time period in the planning horizon

$D_{k,c}$: Demand of order k, for customer c

LT_k : Lead time for order k

WR : Weight of total reliability in the multi-objective model

WC : Weight of total cost in the multi-objective model

Zmin: Minimum lot size for a partner to start production, at a time period

TZmin: Minimum total production (processing time) for a partner to start production, at a time period

TTmin: Minimum total transportation (weight) for a partner to transport goods, at a time period

OP_k :Order priority index for order k

MR_n :Manufacturing reliability index for node n

M : Very large number

K : Total number of customer orders

N : Total number of manufacturing partners, (nodes)

A company can be included in the network at three different levels and binary variables will be used to indicate selection or exclusion decisions. In this section we have explained the contents of the associated costs as follows:

- Selecting a manufacturing unit n to an operation i will have a fixed cost *Selection Cost* ($SC_{i,n}$). At this level, it is a cost related with inter-organizational communication and supportive managerial activities. This cost is different from the integration costs to join the Strategic Partnership (charged directly when joining the long term network).
- Assigning operation i, of company n, to production of order k, will have a fixed cost, *Assignment Cost* ($AC_{k,i,n}$). Examples of order assignment costs include the cost of energy used to operate the factory equipment, costs of factory supplies and the cost of depreciation on the factory equipment and the building.
- Assigning production of order k to operation i, manufacturer n, at time period t, has a *Fixed Production Cost* ($FPC_{t,k,i,n}$). This cost arises directly from manufacturing and processing of production lots, such as the costs of labor to position tools and the costs of materials.
- Assigning transportation from node n to node m has a fixed cost *Fixed Transportation Cost* ($FTC_{n,m}$). This cost is associated with the labor used to prepare the batch for transportation, and the fuel used during transportation.

4.3.3.3. Variables

$Y_{i,n}$: Binary variable, that takes the value 1 if node n, operation i is included into the network;

and takes the value, 0 otherwise

$W_{k,i,n}$: Binary variable, that takes the value 1 if node n, operation i is assigned for

production of order k; and takes value 0 otherwise

$V_{t,k,i,n}$: Binary variable that takes value 1 if node n, operation i is assigned for production of

order k, at time t; and takes the value 0 otherwise

$IF_{t,k,i,n}$: Post-production inventory level of order k, at operation i, node n, at time period t

$IS_{t,k,i,n}$: Pre-production inventory level of order k, at operation i, node n, at time period t

$Z_{t,k,i,n}$: Production lot of order k, at node n of operation i, at time period t

$X_{t,k,i,j,n,m}$: Transportation lot at time t, for order k, from operation i to operation j, from node n to node m

$TT_{t,k,i,j,n,m}$: Binary variable, that takes the value 1 if there is transportation at time t, of order k, from operation i to operation j, from node n to node m; and takes value 0, otherwise

$CD_{k,t,n,c}$: Demand of order k fulfilled at time t, by node n, to customer c

4.3.3.4. Objectives

Two objective functions have been considered in this work_ reliability (to be maximized), based on order priority; and total cost. In this multi-objective approach, we used the standard weighted sum method.

The first objective, *reliability* is computed by multiplying the manufacturing reliability and the order priority indexes, with the associated production lot sizes. This formula assigns more prioritized orders to more reliable manufacturers. With this objective, it is possible to increase order priority weighted reliability of the manufacturing network.

$$Maximize\ Reliability = Max\ (MR_{\ n} \times OP_k \times Z_{tkin})$$

The second objective is *total operational costs* of the Dynamic Manufacturing Network. Total costs involve total pre-operation holding costs, total post operation holding costs, total variable production costs, total fixed production costs, total node selection costs, total order assignment costs, total fixed transportation costs, total variable transportation costs and total shipment costs.

$$Minimize\ Total\ Cost = Min\ (THC + TPC + TNFC + TTC + CTC)$$

$THC\text{: }Total\ Holding\ Cost = (Pre\ Operation\ Hold.Cost + Post\ Operation\ Hold.Cost)$

$$THC = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{O}\sum_{n=1}^{N}\left[HCS_{k,i,n} \times IS_{t,k,i,n}\right] + \left[HCF_{k,i,n} \times IF_{t,k,i,n}\right]$$

$TPC\text{: }Total\ Production\ Cost = (Variable\ Production\ Cost + Fixed\ Production\ Cost)$

$$TPC = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{O}\sum_{k=1}^{K}\left[Z_{t,k,i,n} \times UPC_{i,n} \times UPT_{k,i,n}\right] + \left[V_{t,k,i,n} \times FPC_{k,i,n}\right]$$

$TNFC\text{: }Network\ Formation\ Cost = (Node\ Selection\ Cost + Order\ Assignment\ Cost)$

$$TNFC = \sum_{i=1}^{O}\sum_{n=1}^{N}\left[Y_{i,n} \times SC_{i,n}\right] + \sum_{k=1}^{K}\sum_{i=1}^{O}\sum_{n=1}^{N} W_{k,i,n} \times AC_{k,i,n}$$

$TTC\text{: }Total\ TransportationCost = (Fixed\ Transpt.Cost + Variable\ Transpt.Cost)$

$$TTC = \sum_{t=1}^{T}\sum_{\forall(i,j)\in A}\sum_{\forall n\in N_{i:(i,j)\in A}}\sum_{\forall m\in N_{j:(i,j)\in A}}\left[TT_{t,i,j,n,m} \times FTC_{n,m}\right]$$
$$+ \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{\forall(i,j)\in A_k}\sum_{\forall n\in N_i:(i,j)\in A_k}\sum_{\forall m\in N_j:(i,j)\in A_k}\left[X_{t,k,i,j,n,m} \times UTC_{n,m} \times UW_{i,k}\right]$$

$CTC\text{: }Total\ Shipment\ Cost$

$$CTC = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{c=1}^{C} CD_{k,t,n,c} \times CDTRCOST_{c,n} \times UW_{c,k}$$

4.3.3.5. Constraints

$$\sum_{1}^{K} W_{k,i,n} \geq 1 \qquad \forall i \in O_k;\ \forall n \in N_i \tag{1}$$

Constraint 1 imply that at least one node has to be assigned to each order, for each operation it passes through.

$$\sum_{1}^{K} W_{k,i,n} \leq K \times Y_{i,n} \qquad \forall i \in O_k;\ \forall n \ \in N_i \tag{2}$$

$$\sum_{1}^{K} W_{k,i,n} \ \geq 1 - K \ \times \ \left(1 - Y_{i,n}\right) \qquad \forall i \in O_k;\ \forall n \in N_i \tag{3}$$

Constraints 2.1 and 2.2 provide the link between selection of a manufacturing unit, and its assignment to a product. These inequalities together imply that if an operation of a manufacturing unit is assigned to at least one product, that operation should be included into the network. An operation of a manufacturing unit is allowed to be assigned to more than one product.

$$\sum_{1}^{T} V_{t,k,i,n} \leq T \times W_{k,i,n} \qquad \forall k \in K;\ \forall i \in O_k;\ \forall n \in N_i \tag{4}$$

$$\sum_{1}^{T} V_{t,k,i,n} \ \geq 1 - T \times \left(1 - W_{k,i,n}\right) \qquad \forall k \in K;\ \ \forall i \in \ O_k;\ \forall n \in N_i \tag{5}$$

Constraints 3.1 and 3.2 imply that a node can only produce a given order k at time t, if that operation is already assigned to that order.

$$\sum_{k=1}^{K} Z_{t,k,i,n} \times UPT_{k,i,n} \ \leq CAP_{t,i,n} \qquad \forall t \in T;\ \forall i \in O_k;\ \forall n \in N_i \tag{6}$$

$$Z_{t,k,i,n} \ \leq CAP_{t,i,n} \times V_{t,k,i,n} \qquad \forall t \in T; \forall k \in K;\ \ \forall i \in \ O_k;\ \forall\ n \in \ \ N_i \tag{7}$$

$$Z_{t,k,i,n} \ \geq Zmin \times V_{t,k,i,n} \qquad \forall t \in T; \forall k \in K;\ \ \forall i \in \ O_k;\ \forall n \in N_i \tag{8}$$

$$\sum_{k=1}^{K} Z_{t,k,i,n} \times UPT_{k,i,n} \ \geq V_{t,k,i,n} \ \times \ \ TZmin \qquad \forall t \in T;\ \forall i \in \ O_k; \forall n \in N_i \tag{9}$$

Constraints 4.1 and 4.2 aim to balance production lots with capacities. While constraints 4.1 guarantee that total production times of all products assigned to an operation of a manufacturing node, at a particular time period, do not exceed total capacity; constraints 4.2 relate production lot sizing decisions with binary production assignment variables. Constraints 4.3 ensure the satisfaction of minimum production lot requirement, and constraints 4.4 ensure the minimum total processing time required by each node, for each time period.

$$\sum_{t=1}^{T}\sum_{m=1}^{N}\sum_{\forall j:(i,j)\in A_k} X_{t,k,i,j,n,m} \leq W_{k,i,n} \times M \qquad \forall k \in K; \forall i,j \in O_k;\ \forall n,m \in N_i;\ \forall t \in T \tag{10}$$

$$\sum_{k=1}^{K} X_{t,k,i,j,n,m} \times UW_{i,k} \leq TRCAP_{n,m} \times TT_{t,i,j,n,m} \quad \forall k \in K; \forall i,j \in O_k;\ \forall n,m \in N_i;\ \forall t \in T \tag{11}$$

$$\sum_{k=1}^{K} X_{t,k,i,j,n,m} \times UW_{i,k} \geq TTmin \times TT_{t,i,j,n,m} \quad \forall k \in K; \forall i,j \in O_k;\ \forall n,m \in N_i;\ \forall t \in T \tag{12}$$

Constraints 5.1 impose that, in order to transport a product from a node, that node has to be assigned to that product. Constraints 5.2 ensure that, the total transported amount will not go over the transportation capacity. Constraints 5.3 guarantee the satisfaction of minimum total weight required to start transportation, at a time period.

$$IS_{t,k,i=1,n} = IS_{t-1,k,i=1,n} - Z_{t,k,i=1,n}\ ; \quad \forall k \in K; \forall\ i = 1;\ \forall n \in N_{i=1}\ ;\ \forall t \in T \tag{13}$$

$$IS_{t,k,j,m} = IS_{t-1,k,j,m} - Z_{t,k,j,m} + \sum_{\forall\, n \in N_{i:(i,j)\in A_k}} X_{t-1,k,i,j,n,m;}\ ;\ \forall k \in K;\ \forall i,j \in O_k \&\ j \neq 1; \forall m \in N_{j:(i,j)\in A_k};\ \forall t \in\ T \tag{14}$$

Flow balancing for raw material inventory is expressed by constraint 6.1s for echelon 1, and by constraints 6.2 for the other echelons.

$$IF_{t,k,i,n} = IF_{t-1,k,i,n} + Z_{t-1,k,i,n} - \sum_{\forall\, m \in N_{j:(i,j)\in A_k}} X_{t-1,k,i,j,n,m;}\quad ; \forall k \in K; \forall i,j \in O_k \&\ i \neq O;\ \forall n\ \in N_{i:(i,j)\in A_k};\ \forall t \in T \tag{15}$$

$$IF_{t,k,i=O,n} = IF_{t-1,k,i=O,n} + Z_{t-1,k,i=O,n};\ \ \forall k \in K;\ \forall n \in N_O;\ \forall t \in 1..LT_k \tag{16}$$

$$IF_{t,ki=,O,n} + Z_{t,k,i=O,n} = \sum_{c=1}^{C} CD_{k,t,n,c}\ ; \qquad \forall k \in K;\ \forall n \in N_O;\ \forall t = LT_k \tag{17}$$

Constraints 7.1 are the finishing inventory flow equations, for all echelons, except for the last echelon. Constraints 7.2 are the finishing inventory flow equations for the last echelon. And constraints 7.3 are the flow equations for demand fulfilment, from the last echelon to the customers.

$$\sum_{n=1}^{N} CD_{k,t,n,c} = D_{k,c}\ ; \quad \forall c \in C; \quad \forall k \in K;\ \forall n \in N_O;\ \forall t = LT_k \tag{18}$$

$$\sum_{k=1}^{K} CD_{k,t,n,c} \times UW_{i=O,k} \leq CDTRCAP_{c,n}\ ; \forall c \in C; \quad \forall k \in K;\ \forall n \in N_O \tag{19}$$

Constraints 8.1 ensure that the total delivered goods are equal to the total demand. Constraints 8.2 are the transportation capacity constraints for the last echelon.

$$IF_{0,k,i,n} = 0; \quad IS_{0,k,i,n} = 0; \qquad \forall k \in K; \forall i \in O_k; \forall n \in N_i \tag{9}$$

$$IF_{t,k,i,n}, IS_{t,k,i,n}, Z_{t,k,i,n} \geq 0; \qquad \forall t \in T; \forall k \in K; \forall i \in O_k; \forall n \in N_i \tag{10}$$

$$X_{t,k,i,j,n,m} \geq 0; \qquad \forall t \in T; \forall\, k \in K; \forall\, (i,j) \in A_k;\ \forall n \in N_{i:(i,j)\in A_k};\ \forall m \in N_{j:(i,j)\in A_k} \tag{11}$$

$$Y_{i,n} \in \{0,1\}; \qquad \forall i \in O_k;\ \forall n \in N_i \tag{12}$$

$$W_{k,i,n} \in \{0,1\}; \qquad \forall k \in K;\ \forall i \in O_k;\ \forall n \in N_i \tag{13}$$

$$V_{t,k,i,n} \in \{0,1\}; \qquad \forall t \in T;\ \forall k \in K;\ \forall i \in O_k;\ \forall n \in N_i \tag{14}$$

$$TT_{t,k,i,j,n,m} \in \{0,1\}; \qquad \forall t \in T; \forall\, k \in K; \forall\, (i,j) \in A_k;\ \forall n \in N_{i:(i,j)\in A_k};\ \forall m \in N_{j:(i,j)\in A_k} \tag{15}$$

Constraints 9 set the starting inventory levels as 0, and constraints 10-15 define the types of the different decision variables.

4.4. Illustrative Example

For illustrative purposes, in this section we apply our integrated approach to a problem instance that, although small, is hopefully representative of some real situations.

4.4.1. Indexes Calculation

In this example, we have considered formation of a DMN composed by 8 customers, 10 orders and 12 manufacturers. Table 13, Table 14 and Table 15 present the weights for the different criteria, and the values of the three indexes (manufacturing reliability, order criticality and customer reliability).

Table 13 is the Customer Priority decision Matrix. The criteria involved are: average worth of all orders, order frequency per year, collaboration time, customer Size, average profit from given orders, on time payment and average delay in payments.

Table 14 is the Order Criticality decision matrix, which covers: due date, total slack time, total number of operations, lot size, and value. Since DMNs are order driven networks, components of the order criticality data initiate the DMN formation process.

Table 15 presents the Manufacturer Reliability decision matrix, covering the following criteria: on time delivery ratio, total contribution in terms of order produced the year before, managerial assessment, average delays the year before, rejected order last year, adequate quality from last year and frequency of selection to a DMN last year.

These decision matrices are used to compute the indexes, with TOPSIS. Initially we have created the decision matrices as presented. Then, we have computed normalized decision matrixes through a distributive normalization. The next step was to calculate the weighted standard decision matrices, by multiplying each matrix element by the associated criterion weight. At step four, we have computed ideal points. At step five, the distance from each action to the ideal solution is computed as an Euclidian distance. Finally, the indexes are computed and ranked according to their value. The computed final index allows us to rank each alternative on a scale of 0-1.

Table 13 Customer Priority Decision matrix

Ai/Cj	Average value of all orders (Euros)	Order frequency per year	Collaboration time (weeks)	Customer Size (1-10)	Average profit from given orders (percent)	On time Payment (Ratio)	Average delay in payments (weeks)
C1	373,473	14	141	10	15	46	5
C2	570,921	11	78	3	30	83	3
C3	789,198	7	149	4	19	80	2
C4	750,134	30	95	9	13	91	7
C5	429,835	29	106	5	46	98	5
C6	353,523	10	94	2	31	82	2
C7	320,502	30	148	6	38	69	6
C8	716,655	27	96	7	24	32	5
Weights	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.10**

Table 14 Order Criticality Decision matrix

Ai/Cj	Due date (weeks)	Total slack time (weeks)	Total number of operations	Lot size	Value (Euros)
K1	6	1	5	100	480,155
K2	6	2	4	100	477,858
K3	6	2	4	100	372,591
K4	6	3	3	100	308,787
K5	6	2	4	100	396,738
K6	6	2	4	100	380,207
K7	6	3	3	100	372,064
K8	6	3	3	100	323,074
K9	6	2	4	100	329,138
K10	6	2	4	100	444,134
Weights	**0.15**	**0.25**	**0.10**	**0.25**	**0.25**

By applying TOPSIS, we found the solutions shown in Table 16. The first column ranks the 12 manufacturers, in terms of reliability (N6 is the most reliable partner, while N5 is the least reliable one). The third column ranks all orders according to their criticality. Among the 10 orders, K1 is found as the most critical one, with a value of 1, since it has the best value for all criteria. On the other hand, order K4 is the least critical one, with a value of 0, since it has the worst value for all criteria. When we look at the values of customer priority (last column), we can see customer 5 has the highest priority, and customer 1 is the least important one..

Table 15 Manufacturer Reliability Decision matrix

Ai/Cj	On time delivery (ratio)	Total contribution last year (volume produced)	Managerial assesment (1-100)	Average delays last year (weeks)	Rejected orders last year (ratio)	Adequate quality last year (ratio)	Frequency of selection to a DMN last year
N1	72	4423	99	0	3	91	26
N2	76	1361	87	2	1	93	16
N3	83	3775	68	3	5	98	15
N4	81	4643	100	0	7	89	20
N5	97	2649	68	2	10	91	20
N6	92	3574	94	0	0	85	26
N7	98	1423	90	0	3	100	21
N8	76	3493	89	2	8	90	12
N9	100	3929	61	3	6	92	5
N10	80	4434	65	2	8	90	25
N11	94	2781	99	2	2	92	8
N12	86	2007	90	1	2	88	11
Weights	**0.25**	**0.10**	**0.20**	**0.10**	**0.10**	**0.20**	**0.05**

Table 16 Indexes and Rankings

Manufacturers	Manufacturer reliability	Orders	Order criticality	Customers	Customer priority
N6	0.84	**K1**	1.00	**C5**	0.88
N1	0.72	**K2**	0.58	**C4**	0.83
N7	0.68	**K10**	0.55	**C2**	0.76
N12	0.62	**K5**	0.50	**C6**	0.74
N4	0.61	**K6**	0.48	**C3**	0.74
N11	0.58	**K3**	0.48	**C7**	0.67
N2	0.52	**K9**	0.43	**C8**	0.31
N10	0.38	**K7**	0.15	**C1**	0.15
N3	0.37	**K8**	0.04		
N9	0.37	**K4**	0.00		
N8	0.36				
N5	0.32				

4.4.2. ORDER PRIORITY

We have built a fuzzy inference system, as shown in Figure 22. The two input parameters "order criticality" and "customer priority" are transformed into triangular fuzzy membership functions, and combined into "order priority" output. As depicted in Figure 23, the triangular fuzzy functions vary in a 0- 1 interval.

We have used MATLAB to compute the fuzzy and crisp values. In order to make this transformation, we have developed 9 fuzzy rules as presented in Figure 24. The members of the strategic partnership (SME Network) decide which rules apply, and any time if their preferences change, it is possible to develop a new inference system, with a different rule base. In this study rules are developed by taking expert opinions as input.

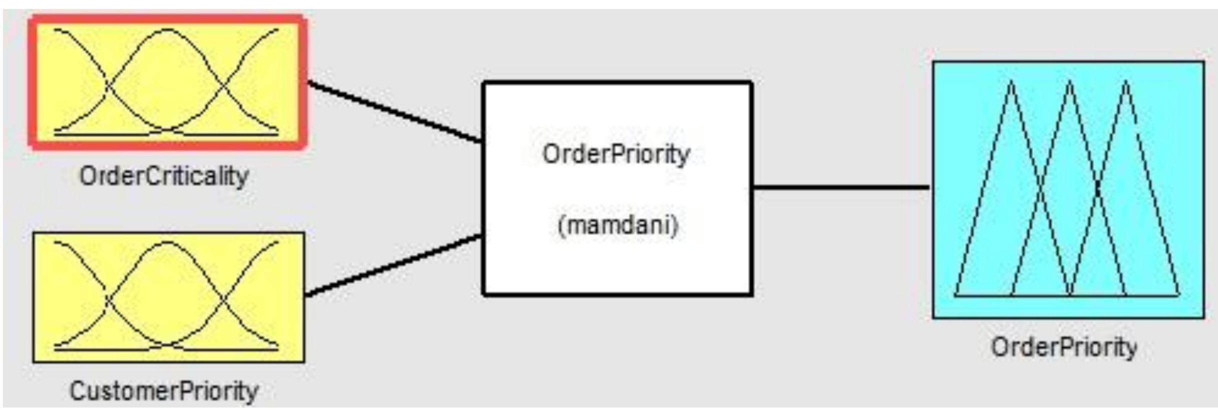

Figure 22 Fuzzy inference system

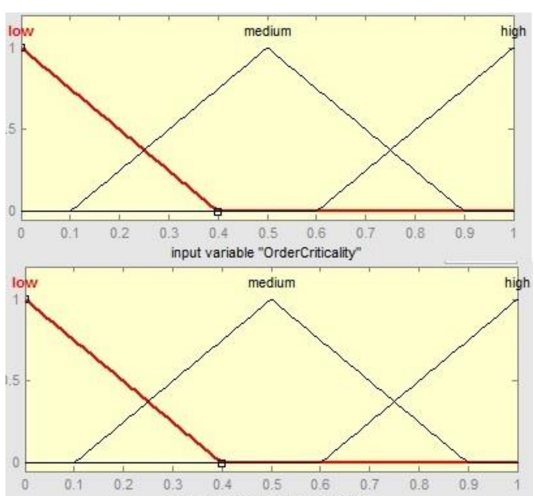

Figure 23 Triangular fuzzy functions

Table 17 presents the outputs of the Fuzzy Inference System, with the computed value for the order criticality, customer priority and order priority.

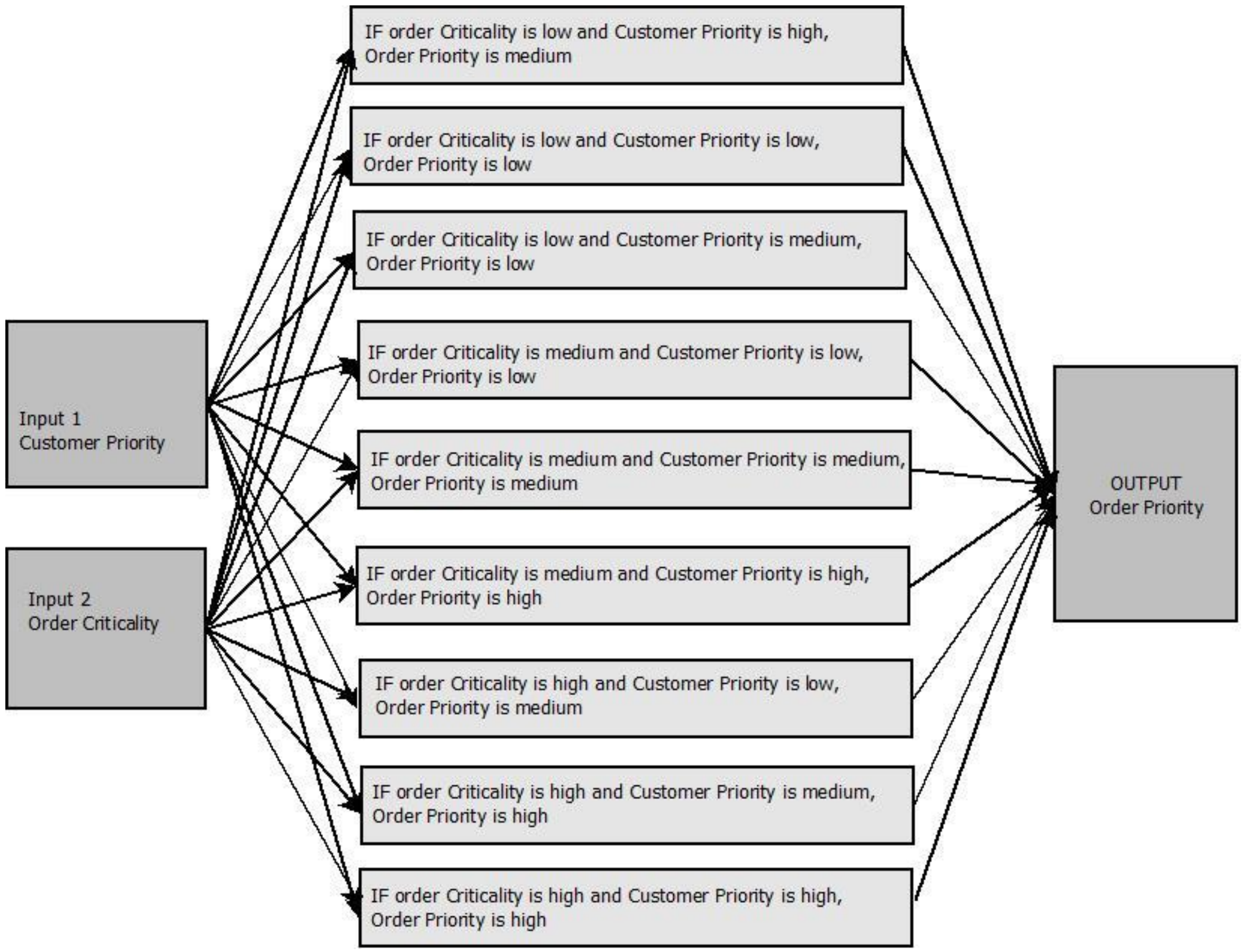

Figure 24 Fuzzy sets and fuzzy rules

Table 17 Inputs and FIS crisp outputs

ORDER	CUSTOMER	Order Criticality	Customer Priority	Order Priority
K1	C1	1.00	0.15	**0.52**
K2	C2	0.58	0.76	**0.60**
K3	C4	0.48	0.83	**0.66**
K4	C3	0.00	0.74	**0.40**
K5	C6	0.50	0.74	**0.59**
K6	C8	0.48	0.31	**0.46**
K7	C7	0.15	0.67	**0.33**
K8	C7	0.04	0.67	**0.29**
K9	C5	0.43	0.88	**0.75**
K10	C5	0.55	0.88	**0.75**

4.4.3. *Network Formation*

4.4.3.1. Computational Tests

To understand the impact of the problem size on the processing times, we have created several data sets based on different numbers of the (see Table 18). While for small instances, such as the first data set, it is possible to reach an optimal solution in a few minutes, for larger instances, such as the last data set, the size of the model grows exponentially, and the computer memory cannot handle its complexity. Although we have not considered it as a part of this study, we believe specific heuristics need to be developed for large instances. In the first three data sets, we have considered different customer and order sizes, while keeping the same network structure. Note that the variations of the processing time of a given instance results from changing the weights of the criteria in the multi-objective approach.

Table 18 Tests instances and processing times

Customers	Orders	Manufacturers	Echelons	Time periods (time 0..6)	Integer decision variables	Binary Decision variables	Processing time (interval)
2	4	12	5	7	106512	27180	1-1.5 mins
8	10	12	5	7	271320	30060	2-3 mins
12	15	12	5	7	412020	32460	3-4 mins
12	15	20	5	7	1106700	82100	15 mins - Out of memory

4.4.3.2. Test Instances

A network structure with 5 echelons (consecutive operations), 12 partners, 10 orders, 8 customers, and 6 time periods, has been considered as an illustrative example. Production starts at time 0, and the first lot can be produced at time 1. We have used a data set (as depicted in Table 19) that is inspired by data collection in a real life case study. Without additional information, values are generated following a uniform distribution. The complete data set can be found in Appendix 1. In this example, the manufacturing reliability, customer priority and order criticality indexes have been computed with the criteria weights given in the Table 13, Table 14 and Table 15.

The demand is shown in Table 20. In order to demonstrate how the network structure responds to changes in order lot sizes and lead times, we have created two values for lot sizes and lead times. While in the first scenario, the lot size and the lead time values for all orders are the same; in the second scenario we have considered different values. Note that lead times in this example, are given in weeks.

Table 19 Data characteristics

Parameter	Data
Selection Cost	Uniform(1000,4000)
Assignment Cost	Uniform (600,1000)
Fixed Production Cost	Uniform (40,80)
Unit Production Cost	Uniform (2,5)
Unit Production Time	Uniform (1,5)
Capacity	Uniform (3000,4000)
Fixed Transportation Cost	Uniform (100,200)
Unit Transportation Cost	Uniform (1,5)
Unit Weight	Uniform (2,8)
Unit Weight to Customer	Uniform (2,7)
Starting Inventory Holding Cost	Uniform (1,3)
Finishing Inventory Holding Cost	Uniform (3,5)
Transportation Capacity	Uniform (300000,700000)
Customer Transportation Capacity	Uniform (200000, 400000)
Customer Unit Transportation Cost	Uniform (3,9)

Table 20 Demand

		Same Values		Different Values	
Order	Customer	Lot Size	Lead Time	Lot Size2	Lead Time2
1	1	100	6	108	6
2	2	100	6	93	6
3	4	100	6	107	5
4	3	100	6	84	6
5	6	100	6	115	5
6	8	100	6	105	5
7	7	100	6	86	5
8	7	100	6	101	6
9	5	100	6	80	5
10	5	100	6	112	6

The orders (K1 to K10 go through subsequences of the five operations. Figure 25 presents the operational configuration of each order. The last echelon stands for the customer, who will receive the final product. For instance, order 1 goes through all operations, and will be delivered to customer 1. Order 2 on the other hand goes through Operations 1, 3, 4 and5. Taking into account the characteristics of each order, it is possible to include and exclude operations in the manufacturing processes.

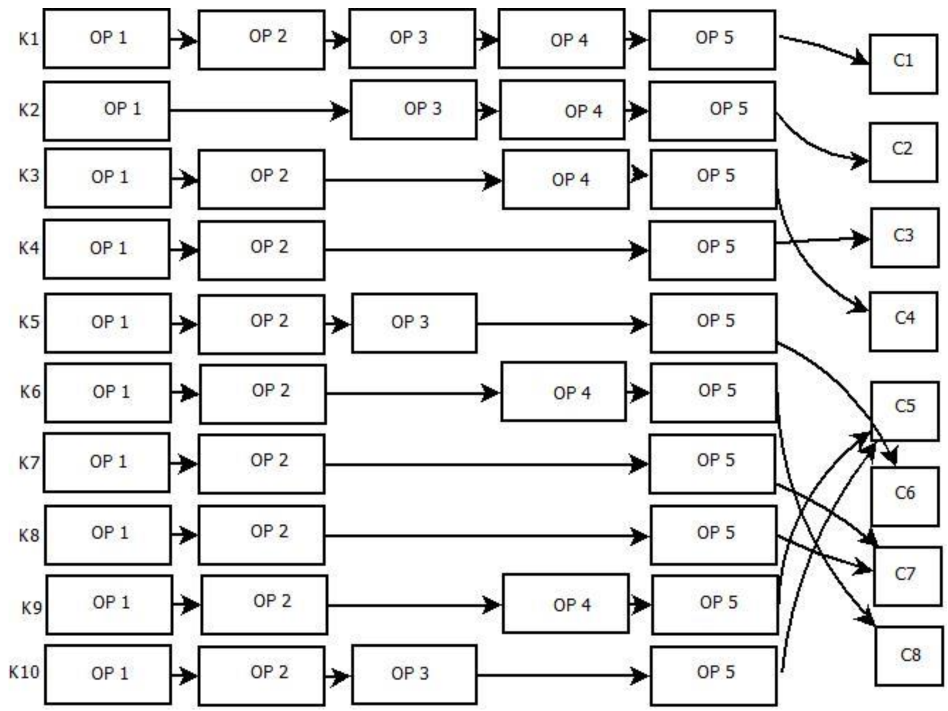

Figure 25 Orders and operational configuration

4.4.3.3. Results

In order to solve this multi-objective MILP model, a simple weighted approach is used. By giving different weights to the two objective functions, we have found different optimal (close to), non-dominated solutions, with different values for the cost and reliability. The weights of the objectives functions must add up to 1.

For validating and assessing the developed approach, we have created four data sets. We have initially observed how different demand sizes and lead times affect the final network structure. The four developed scenarios include: equal order, size equal lead time; equal order size, different lead time; different order size, equal lead time; and different order size, different lead time.

4.4.3.3.1. Equal order size, equal lead time

The pure minimum cost solution (weight of total cost has been taken as 1) has a total value of 140,972, and is composed of partners N3, N6, N8, N9, N10 and N12. The total assignment cost is 32,816, while total production costs are 34,419 (fixed and variable costs included). The total selection cost that is charged for each node to be included into the network is 18,950. The total variable transportation cost is 23,800, while total fixed transportation costs are 2,087. On the other hand, the total cost of transporting finished goods to the customer is 28,900. Moreover, the total reliability value for the minimum cost solution is 1,057. Table 21 includes production lot sizes in the *minimum total cost and the maximum total reliability* solutions.

The pure maximum total reliability solution, on the other hand, has a value of 1,394 and is composed of partners N1, N6, N7, N9 and N12. Moreover, the total cost for this solution is 166,108. The total assignment cost is 32,373, while total Production costs are 42,296 (fixed and variable costs included). The total selection cost that is charged for each node to be included into the network is 13,800. The total variable transportation cost is 31,800, while total fixed transportation costs are 2,039. On the other hand, the total cost of transporting finished goods to the customer is 35,800.

Figure 26 shows the tradeoff between total cost and total reliability, for the equal order size, equal lead time scenario, and Table 22 depicts weights and values used in the multi-objective model. The maximum reliability solution has a cost of 166,110 and a reliability value of 1,394. We have also included in the table, the values for the cost of unit reliability, in order to allow a comparison between different alternative solutions. Initially, as the weight of reliability decreases, the cost of reliability also tends to decrease until solution 5. At this point, the cost of unit reliability is at its minimum (112), with a total cost of 154,910 and total reliability of 1,382. When the weight of cost is in between 0.5 and 0.6, the cost of unit reliability starts to increase and at the minimum cost solution (140,970), the cost of unit reliability increases up to its maximum value (133.37).

Table 21 Production lot sizes for Scenario 1 (same order sizes and lead times)

Minimum Cost					Maximum Reliability				
Time	K	O	N	Lot	Time	K	O	N	Lot
6	K10	O5	N10	100	6	K2	O5	N12	100
6	K9	O5	N10	100	5	K7	O5	N12	100
6	K8	O5	N12	100	5	K3	O5	N12	100
6	K7	O5	N12	100	5	K2	O4	N9	100
6	K6	O5	N10	100	5	K1	O5	N12	100
6	K5	O5	N10	100	4	K10	O5	N12	100
6	K4	O5	N10	100	4	K9	O5	N12	100
6	K3	O5	N12	100	4	K6	O5	N12	100
6	K2	O5	N12	100	4	K5	O5	N12	100
6	K1	O5	N12	100	4	K3	O4	N9	100
5	K10	O3	N8	100	4	K2	O3	N7	100
5	K9	O4	N9	100	4	K1	O4	N9	100
5	K8	O2	N6	100	3	K10	O3	N7	100
5	K7	O2	N6	100	3	K9	O4	N9	100
5	K6	O4	N9	100	3	K8	O5	N12	100
5	K5	O3	N8	100	3	K6	O4	N9	100
5	K4	O2	N6	100	3	K5	O3	N7	100
5	K3	O4	N9	100	3	K4	O5	N12	100
5	K2	O4	N9	100	3	K3	O2	N6	100
5	K1	O4	N9	100	3	K1	O3	N7	100
4	K10	O2	N6	100	2	K10	O2	N6	100
4	K9	O2	N6	100	2	K9	O2	N6	100
4	K8	O1	N3	100	2	K8	O2	N6	100
4	K7	O1	N3	100	2	K7	O2	N6	100
4	K6	O2	N6	100	2	K6	O2	N6	100
4	K5	O2	N6	100	2	K5	O2	N6	100
4	K4	O1	N3	100	2	K4	O2	N6	100
4	K3	O2	N6	100	2	K2	O1	N1	100
4	K2	O3	N8	100	2	K1	O2	N6	100
4	K1	O3	N8	100	1	K10	O1	N1	100
3	K10	O1	N3	100	1	K9	O1	N1	100
3	K9	O1	N3	100	1	K8	O1	N1	100
3	K6	O1	N3	100	1	K7	O1	N1	100
3	K5	O1	N3	100	1	K6	O1	N1	100
3	K3	O1	N3	100	1	K5	O1	N1	100
3	K2	O1	N3	100	1	K4	O1	N1	100
3	K1	O2	N6	100	1	K1	O1	N1	100
2	K1	O1	N3	100	2	K3	O1	N1	50
					1	K3	O1	N1	50

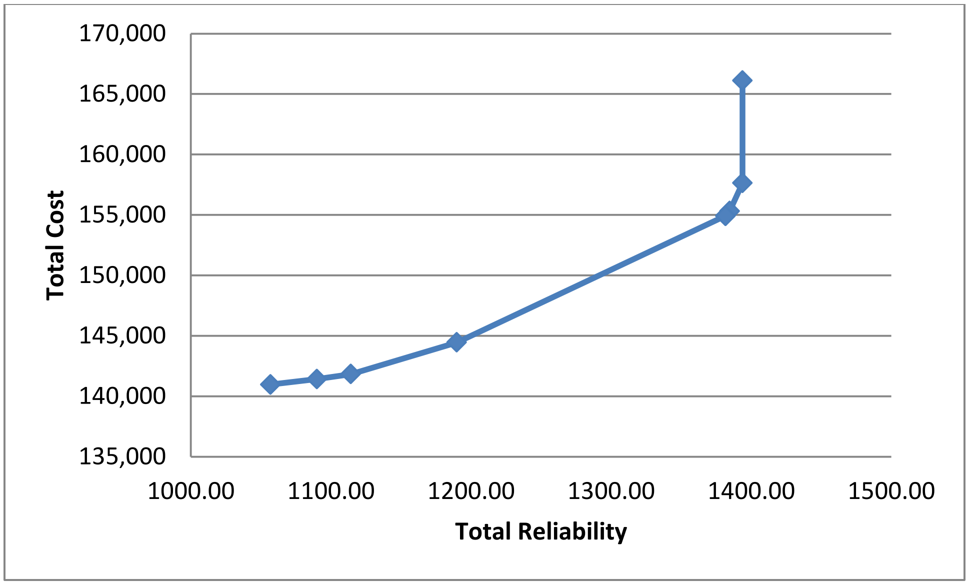

Figure 26 Tradeoff between total cost and total reliability in Scenario 1

Table 22 Weights and values for the multi-objective model in Scenario 1

Solution	W cost	W reliability	Total reliability	Total cost	Cost of unit reliability
1	0.00	1.00	1393.80	166,110	119.18
2	0.10	0.90	1393.80	157,630	113.09
3	0.20	0.80	1384.70	155,310	112.16
4	0.30	0.70	1384.70	155,310	112.16
5	0.40	0.60	1381.70	154,910	112.12
6	0.50	0.50	1381.70	154,910	112.12
7	0.60	0.40	1189.80	144,450	121.41
8	0.70	0.30	1114.20	141,820	127.28
9	0.80	0.20	1090.10	141,410	129.72
10	0.90	0.10	1057.00	140,970	133.37
11	1.00	0.00	1057.00	140,970	133.37

4.4.3.3.2. Equal order size, different lead time

The pure minimum cost solution has a total cost of 141,181 and is composed of partners N3, N6, N8, N9, N10 and N12. The total assignment cost is 33,074, while the total production costs are 33,935 (both fixed and variable costs included). The total selection cost that is charged for each node to be included into the network is 18,950. The total variable transportation cost is 24,200, while the total fixed transportation costs are 1,922. On the other hand, the total cost of transporting finished goods to the customer is 28,900.

Table 24 presents production lot sizes in the *minimum total cost* and *maximum total reliability* solutions. Moreover, the total reliability value for minimum cost solution is found as 1,130.

The pure maximum total reliability solution, on the other hand, has a value of 1,509 and is composed of partners N1, N6, N7, N9 and N12. Moreover, the total cost for this solution is 163,750. The total assignment cost is 32,373, while the total production costs are 42,240 (fixed and variable costs included). The total selection cost that is charged for each node to be included into the network is 13,800. The total variable transportation cost is 31,800, while total fixed transportation costs are 1,933. On the other hand, the total cost of transporting finished goods to the customer is 35,800.

Table 23 Weights and values for the multi-objective model in Scenario 2

Solution	W cost	W reliability	Total reliability	Total cost	Cost of unit reliability
1	0.00	1.00	1508.60	163,750	108.54
2	0.10	0.90	1508.60	158,080	104.79
3	0.20	0.80	1498.90	155,580	103.80
4	0.30	0.70	1495.70	155,040	103.66
5	0.40	0.60	1495.70	155,040	103.66
6	0.50	0.50	1453.50	152,560	104.96
7	0.60	0.40	1285.50	144,575	112.47
8	0.70	0.30	1207.10	142,500	118.05
9	0.80	0.20	1171.30	141,490	120.80
10	0.90	0.10	1146.40	141,180	123.15
11	1.00	0.00	1130.40	141,180	124.89

Figure 27 shows the tradeoff between total cost and total reliability, for the scenario and Table 23 depicts weights and values used in the multi-objective model. Maximum reliability solution has a cost of 163,750 and a reliability value of 1,509. We have also with the table, the values for the cost of unit reliability, in order to allow a comparison between different alternative solutions. Initially, as the weight of reliability decreases, the cost of reliability also tends to decrease until solution 4. At this point, the cost of unit reliability is at its minimum (103.66) with a total cost of 155,040 and a total reliability of 1,496.

Table 24 Production lot sizes for Scenario 2 (equal orders sizes and different lead times)

Minimum Cost					Maximum Reliability				
time	K	O	N	Lot	time	K	O	N	Lot
6	K10	O5	N10	100	6	K8	O5	N12	100
6	K8	O5	N12	100	5	K8	O2	N6	100
6	K4	O5	N10	100	5	K7	O5	N12	100
6	K2	O5	N12	100	5	K1	O5	N12	100
6	K1	O5	N12	100	4	K10	O5	N12	100
5	K9	O5	N10	100	4	K9	O5	N12	100
5	K8	O2	N6	100	4	K6	O5	N12	100
5	K7	O5	N12	100	4	K5	O5	N12	100
5	K6	O5	N10	100	4	K3	O5	N12	100
5	K5	O5	N10	100	4	K2	O5	N12	100
5	K4	O2	N6	100	4	K1	O4	N9	100
5	K3	O5	N10	100	3	K10	O3	N7	100
5	K2	O4	N9	100	3	K9	O4	N9	100
5	K1	O4	N9	100	3	K7	O2	N6	100
4	K10	O3	N8	100	3	K6	O4	N9	100
4	K9	O4	N9	100	3	K5	O3	N7	100
4	K8	O1	N3	100	3	K4	O5	N12	100
4	K7	O2	N6	100	3	K3	O4	N9	100
4	K6	O4	N9	100	3	K2	O4	N9	100
4	K5	O3	N8	100	3	K1	O3	N7	100
4	K4	O1	N3	100	2	K10	O2	N6	100
4	K3	O4	N9	100	2	K9	O2	N6	100
4	K2	O3	N8	100	2	K8	O1	N1	100
4	K1	O3	N8	100	2	K7	O1	N1	100
3	K10	O2	N6	100	2	K6	O2	N6	100
3	K9	O2	N6	100	2	K5	O2	N6	100
3	K6	O2	N6	100	2	K4	O2	N6	100
3	K5	O2	N6	100	2	K3	O2	N6	100
3	K3	O2	N6	100	2	K2	O3	N7	100
3	K2	O1	N3	100	2	K1	O2	N6	100
3	K1	O2	N6	100	1	K10	O1	N1	100
2	K10	O1	N3	100	1	K9	O1	N1	100
2	K9	O1	N3	100	1	K6	O1	N1	100
2	K7	O1	N3	100	1	K5	O1	N1	100
2	K6	O1	N3	100	1	K4	O1	N1	100
2	K5	O1	N3	100	1	K3	O1	N1	100
2	K3	O1	N3	100	1	K2	O1	N1	100
2	K1	O1	N3	100	1	K1	O1	N1	100

When the weight of cost objective function is between 0.4 and 0.5, the cost of unit reliability starts to increase, and at the minimum cost solution (141.180), the cost of unit reliability increases up to 124.89.

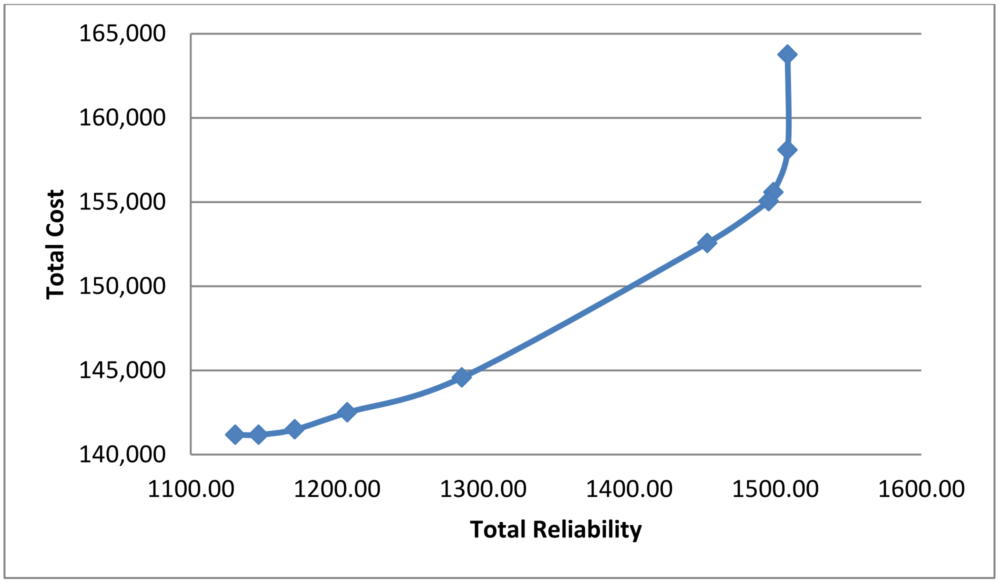

Figure 27 Tradeoff between total cost and total reliability in Scenario 2

4.4.3.3.3. Different order Size, equal lead time

The pure minimum cost solution has a total cost of 141,417, and is composed of partners N3, N6, N8, N9, N10 and N12. The total assignment cost is 32,816, while the total production costs are 34,803. The total Selection cost that is charged for each node to be included into the network is 18,950. The total Variable transportation cost is 23,561, while the total fixed transportation costs are 2,087. On the other hand, the total cost of transporting finished goods to the customer is 29,200. Table 25 includes the production lot sizes in the *minimum total cost and maximum total reliability* solutions. Moreover, the total reliability value for minimum cost solution is 1.106.

The pure maximum total reliability solution, on the other hand. has a value of 1,459and is composed of partners N1, N6, N7, N9 and N12. Moreover, the total cost for this solution is 166,040. The total assignment cost is 32,373, while the total production costs are 42,192 (both fixed and variable costs included). The total selection cost which is charged for each node to be included into the network is 13,800. The total variable transportation cost is

32,267, while total fixed transportation costs are 1,865. On the other hand, the total cost of transporting finished goods to the customer is 35,671.

Table 25 Production lot sizes for Scenario 3 (different order sizes and equal lead times)

Minimum Cost					Maximum Reliability				
time	**K**	**O**	**N**	**ot**	**time**	**K**	**O**	**N**	**lot**
6	K5	O5	N10	115	4	K5	O5	N12	115
5	K5	O3	N8	115	3	K5	O3	N7	115
4	K5	O2	N6	115	2	K5	O2	N6	115
3	K5	O1	N3	115	1	K5	O1	N1	115
6	K10	O5	N10	112	4	K10	O5	N12	112
5	K10	O3	N8	112	3	K10	O3	N7	112
4	K10	O2	N6	112	2	K10	O2	N6	112
3	K10	O1	N3	112	1	K10	O1	N1	112
6	K1	O5	N12	108	5	K1	O5	N12	108
5	K1	O4	N9	108	4	K1	O4	N9	108
4	K1	O3	N8	108	3	K1	O3	N7	108
3	K1	O2	N6	108	2	K1	O2	N6	108
2	K1	O1	N3	108	1	K1	O1	N1	108
6	K3	O5	N12	107	4	K3	O5	N12	107
5	K3	O4	N9	107	3	K3	O4	N9	107
4	K3	O2	N6	107	2	K3	O2	N6	107
3	K3	O1	N3	107	1	K3	O1	N1	107
6	K6	O5	N10	105	4	K6	O5	N12	105
5	K6	O4	N9	105	3	K6	O4	N9	105
4	K6	O2	N6	105	2	K6	O2	N6	105
3	K6	O1	N3	105	1	K6	O1	N1	105
6	K8	O5	N12	101	3	K8	O5	N12	101
5	K8	O2	N6	101	2	K8	O2	N6	101
4	K8	O1	N3	101	1	K8	O1	N1	101
6	K2	O5	N12	93	6	K2	O5	N12	93
5	K2	O4	N9	93	4	K2	O4	N9	93
4	K2	O3	N8	93	3	K2	O3	N7	93
3	K2	O1	N3	93	1	K2	O1	N1	93
6	K7	O5	N12	86	5	K7	O5	N12	86
5	K7	O2	N6	86	4	K7	O2	N6	86
4	K7	O1	N3	86	3	K4	O5	N12	84
6	K4	O5	N10	84	2	K4	O2	N6	84
5	K4	O2	N6	84	1	K4	O1	N1	84
4	K4	O1	N3	84	5	K9	O5	N12	80
6	K9	O5	N10	80	4	K9	O4	N9	80
5	K9	O4	N9	80	3	K9	O2	N6	80
4	K9	O2	N6	80	2	K9	O1	N1	80
3	K9	O1	N3	80	1	K7	O1	N1	46

Table 26 Weights and values for the multi -objective model in Scenario 3

Solution	W cost	W reliability	Total reliability	Total cost	Cost of unit reliability
1	0.00	1.00	1458.90	166,040	113.81
2	0.10	0.90	1458.90	157,870	108.21
3	0.20	0.80	1450.20	155,760	107.41
4	0.30	0.70	1450.20	155,760	107.41
5	0.40	0.60	1446.60	155,310	107.36
6	0.50	0.50	1399.90	152,300	108.79
7	0.60	0.40	1248.00	144,580	115.85
8	0.70	0.30	1168.40	141,990	121.53
9	0.80	0.20	1168.40	141,990	121.53
10	0.90	0.10	1143.20	141,650	123.91
11	1.00	0.00	1105.80	141,420	127.89

Figure 28 shows the tradeoff between total cost and total reliability, for Scenario 3 and Table 26 depicts weights and values used in the multi objective model.

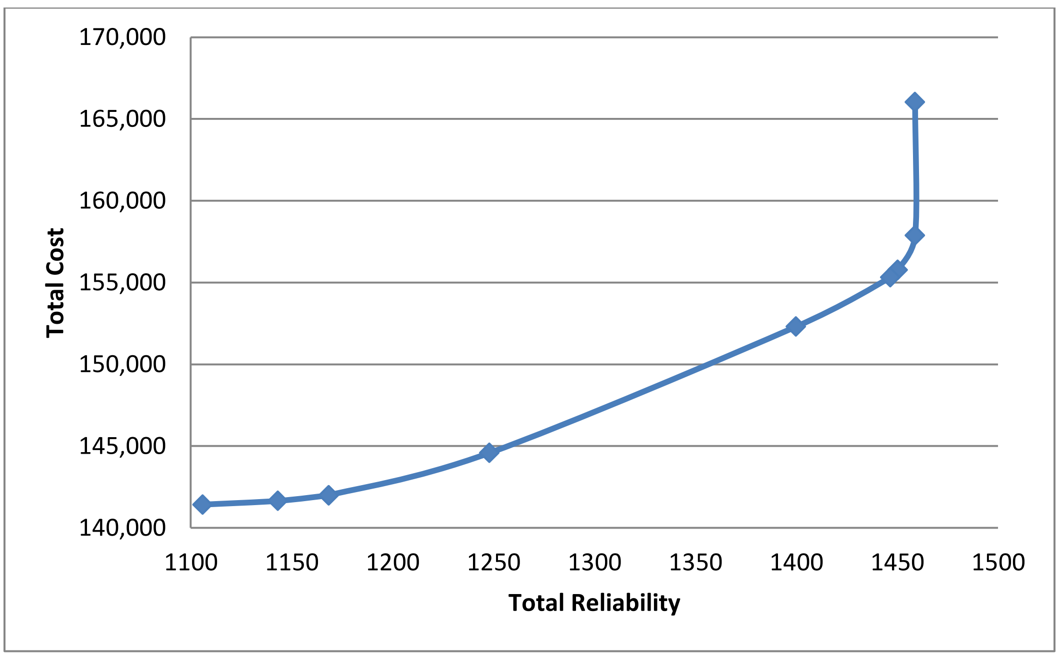

Figure 28 Tradeoff between total cost and total reliability in Scenario 3

The maximum reliability solution has a cost of 166,040 and a reliability value of 1,459. We have also included in the table, the values for the cost of unit reliability, in order to allow comparison between different alternative solutions. Initially, as the weight of reliability decreases, the cost of reliability also tends to decrease, until solution 5. At this point, the cost of unit reliability is at its minimum with a total cost of 155,310 and total reliability of 1,447. When the weight of cost is in between 0.5 and 0.6, the cost of unit reliability starts to increase and at the minimum cost solution (141.420), the cost of unit reliability increases up to its maximum value (127.89).

4.4.3.3.4. Different order size, different lead time

The pure minimum cost solution, in this scenario, has a total cost of 141,617 and is composed of partners N3, N6, N8, N9, N10 and N12. The total assignment cost is 33,074, while the total production costs are 34,284 (both fixed and variable costs included). The total selection cost that is charged for each node to be included into the network is 18,950. The total variable transportation cost is 23,989, while the total fixed transportation costs are 1,922. On the other hand, the total cost of transporting finished goods to the customer is 29,200. Table 28 includes the production lot sizes in the *minimum total cost and maximum total reliability* solutions. Moreover, the total reliability value for the minimum cost solution is 1,146.

The pure maximum total reliability solution, on the other hand, has a value of 1,534and is composed of partners N1, N6, N7, N9 and N12. Moreover, the total cost for this solution is 163,560. The total assignment cost is 32,373, while the total production costs are 42,322. The total Selection cost that is charged for each node to be included into the network is 13,800. The total variable transportation cost is 32,267, while the total fixed transportation costs are 2,082. On the other hand, the total cost of transporting finished goods to the customers is 35,671.

Figure 29 shows the tradeoff between total cost and total reliability, for Scenario 4, and Table 27 depicts weights and values used in the multi-objective model. The maximum reliability solution has a cost of 163,560 and reliability value of 1,534. We have also included with the table, the values for the cost of unit reliability, in order to allow a comparison of different alternative solutions.

Table 27 Weights and values for the multi-objective Model in Scenario 4

Solution	W cost	W reliability	Total reliability	Total cost	Cost of unit reliability
1	0.00	1.00	1534.40	163,560	106.60
2	0.10	0.90	1534.40	158,350	103.20
3	0.20	0.80	1525.20	156,070	102.33
4	0.30	0.70	1521.60	155,440	102.16
5	0.40	0.60	1521.60	155,440	102.16
6	0.50	0.50	1475.00	152,430	103.34
7	0.60	0.40	1283.00	143,760	112.05
8	0.70	0.30	1229.50	142,160	115.62
9	0.80	0.20	1229.50	142,160	115.62
10	0.90	0.10	1162.90	141,630	121.79
11	1.00	0.00	1145.70	141,620	123.61

Initially, as the weight of reliability decreases, the cost of reliability also tends to decrease, until solution 4. At this point, the cost of unit reliability is at its minimum (102.16), with a total cost of 155,440 and a total reliability of 1.522. When the weight of cost is between 0.5 and 0.6, the cost of unit reliability starts to increase, and at the minimum cost solution (141.620), the cost of unit reliability increases up to 123.61.

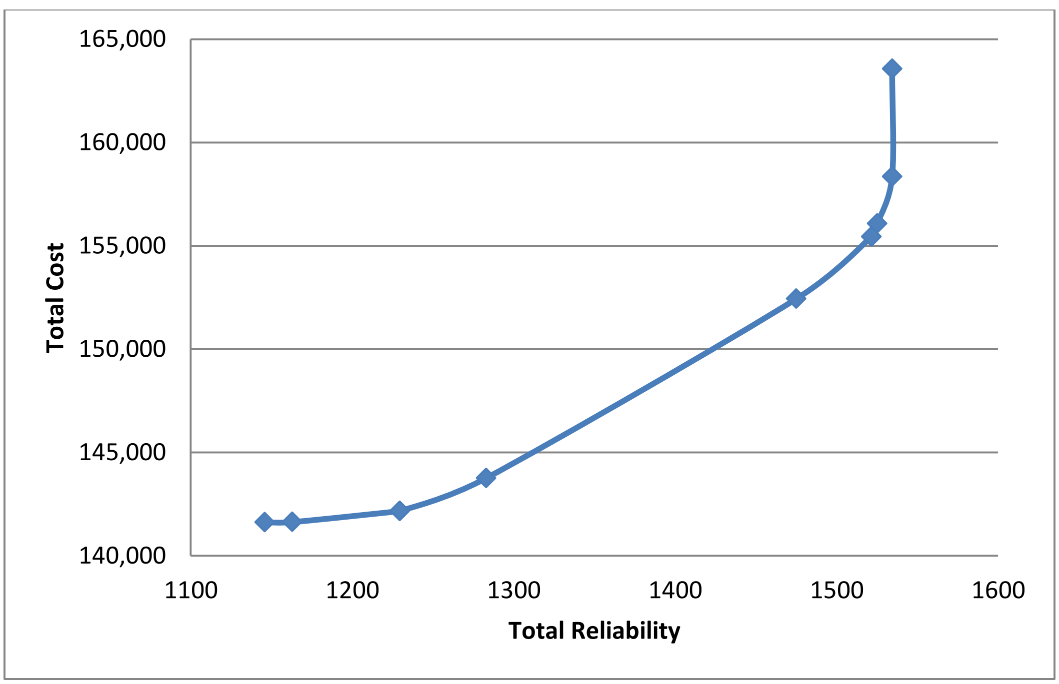

Figure 29 Tradeoff between total cost and total reliability in Scenario 4

Table 28 Production lot sizes for Scenario 4 (different orders sizes and different lead times)

Minimum Cost					Maximum Reliability				
time	**K**	**O**	**N**	**Lot**	**time**	**K**	**O**	**N**	**Lot**
5	K5	O5	N10	115	4	K5	O5	N12	115
4	K5	O3	N8	115	3	K5	O3	N7	115
3	K5	O2	N6	115	2	K5	O2	N6	115
2	K5	O1	N3	115	1	K5	O1	N1	115
6	K10	O5	N10	112	4	K10	O5	N12	112
4	K10	O3	N8	112	3	K10	O3	N7	112
3	K10	O2	N6	112	2	K10	O2	N6	112
2	K10	O1	N3	112	1	K10	O1	N1	112
6	K1	O5	N12	108	5	K1	O5	N12	108
5	K1	O4	N9	108	4	K1	O4	N9	108
4	K1	O3	N8	108	3	K1	O3	N7	108
3	K1	O2	N6	108	2	K1	O2	N6	108
2	K1	O1	N3	108	1	K1	O1	N1	108
5	K3	O5	N10	107	4	K3	O5	N12	107
4	K3	O4	N9	107	3	K3	O4	N9	107
3	K3	O2	N6	107	2	K3	O2	N6	107
2	K3	O1	N3	107	1	K3	O1	N1	107
5	K6	O5	N10	105	4	K6	O5	N12	105
4	K6	O4	N9	105	3	K6	O4	N9	105
3	K6	O2	N6	105	2	K6	O2	N6	105
2	K6	O1	N3	105	1	K6	O1	N1	105
6	K8	O5	N12	101	6	K8	O5	N12	101
5	K8	O2	N6	101	5	K8	O2	N6	101
4	K8	O1	N3	101	1	K8	O1	N1	101
6	K2	O5	N12	93	4	K2	O5	N12	93
5	K2	O4	N9	93	3	K2	O4	N9	93
4	K2	O3	N8	93	2	K2	O3	N7	93
3	K2	O1	N3	93	1	K2	O1	N1	93
5	K7	O5	N12	86	6	K4	O5	N12	84
4	K7	O2	N6	86	5	K4	O2	N6	84
2	K7	O1	N3	86	2	K4	O1	N1	84
6	K4	O5	N10	84	4	K9	O5	N12	80
5	K4	O2	N6	84	3	K9	O4	N9	80
4	K4	O1	N3	84	2	K9	O2	N6	80
5	K9	O5	N10	80	1	K9	O1	N1	80
4	K9	O4	N9	80	3	K7	O5	N12	46
3	K9	O2	N6	80	2	K7	O2	N6	46
2	K9	O1	N3	80	1	K7	O1	N1	46
					5	K7	O5	N12	40
					4	K7	O2	N6	40
					3	K7	O1	N1	40

4.5. DECISION SUPPORT SYSTEM

To implement the described framework, we have developed a decision support system (DSS) that allows decision makers to design and compare alternative network configurations for varying criteria weights. Each of the three indexes (customer priority, order criticality and manufacturer reliability) is computed through a set of criteria. We have classified these criteria in different sub-groups, in order to provide a guideline to the decision maker and ease the criteria weighting process.

Figure 30, presents the classification of the criteria, for the three indexes. For instance, the criteria to compute customer priority index, is separated into three sub-groups: Potential/Growth, Financial Benefit, and Loyalty. If the decision maker wants to promote loyalty, he/she can give higher weights in the TOPSIS to sub-group components: order frequency and collaboration time. The potential/growth sub-group is about the customer size, which means that, the customer with a higher financial strength should be prioritized. On the other hand, the financial benefit sub-group has to do with financial performance measures such as: the average worth of all orders, the average profit from given orders, on time payment and the average delay in payments.

The criteria associated with the order criticality index have been divided into two sub-groups: Order Value and Scheduling Constraints. If the decision maker considers that the criteria order value is more important than the scheduling constraints, he/she can give higher weight to order value in TOPSIS. Scheduling constraints sub-group includes the criteria: due date, total slack time, total number of operations, and lot size. Finally, the criteria used to compute the manufacturer reliability index, have been divided into two sub-groups: Past Performance and Loyalty. While past performance is about how well each manufacturer performed within past DMNs, loyalty is about their overall contribution in the strategic partnership. The past performance sub-group covers on time delivery, total contribution, managerial assessment, average delays and adequate quality criteria. On the other hand, loyalty sub-group consists of the criteria, rejected order (last year) and the frequency of selection to a DMN.

In order to show how the DSS can be utilized, we have built an illustrative example. By taking into account different subjective judgements of the decision makers, we have designed and assesed 12 different DMN configurations.

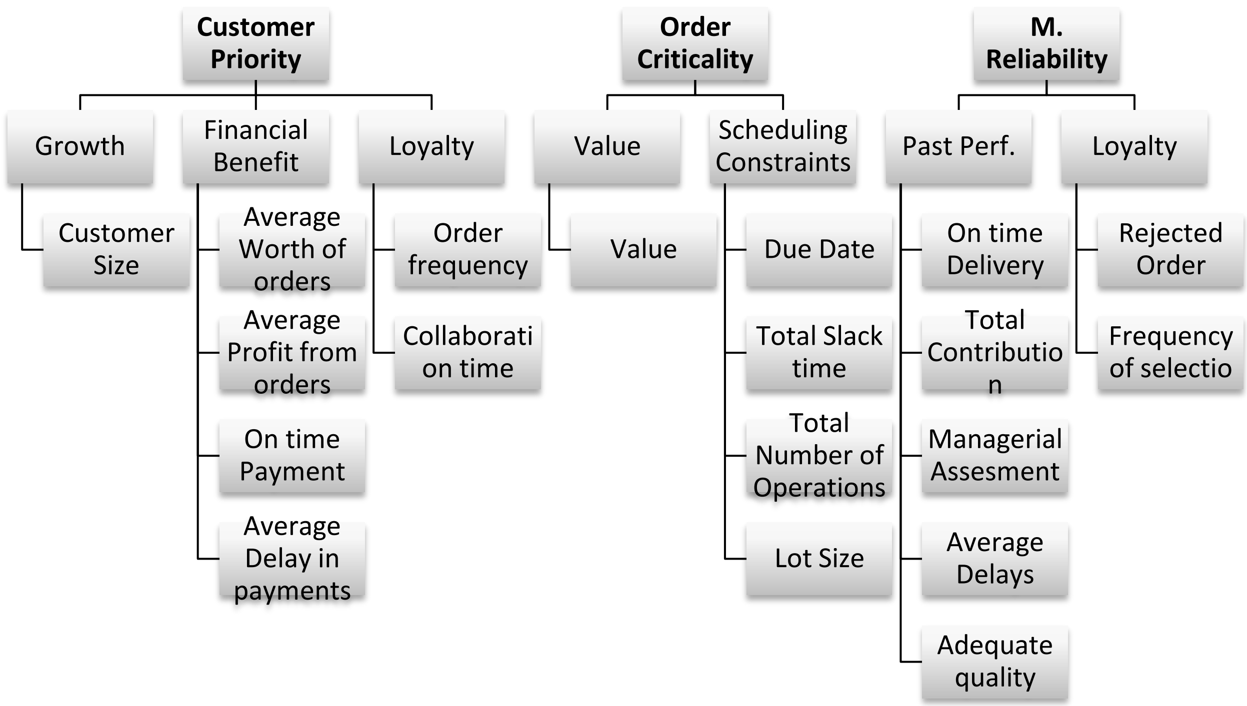

Figure 30 Classification of the criteria

In Table 29, the criteria weights taken for different solutions have been presented. Table 30, on the other hand, shows the solutions to 12 different TOPSIS weight configurations. In the weights section of Table 29, weights of each criteria sub-group are listed.

We have considered that the criteria within each sub-group are weighted equally. For instance, in Configuration 1, the "Potential/growth" sub-group is considered as the dominant criteria in calculating customer priority index with a weight of 40%. The "Potential/ growth" sub-group consists of only one criterion, customer size. So, in configuration 1, the weight of customer size is taken as 40%. On the other hand, in configuration 1, the weight of Financial Benefits is taken as 30%. This sub-group involves 4 criteria: average worth of all orders, average profit from given orders, on time payment and average delay in payments. Each of these four criteria will have a weight of 7.5%.

Table 29 Criteria Weights

	WEIGHTS						
	C. Priority			O. Criticality		M. Reliability	
Solution	**P**	**F**	**LY**	**V**	**S**	**PP**	**LY2**
1	40	30	30	60	40	60	40
2	40	30	30	60	40	40	60
3	40	30	30	40	60	60	40
4	40	30	30	40	60	40	60
5	30	40	30	60	40	60	40
6	30	40	30	60	40	40	60
7	30	40	30	40	60	60	40
8	30	40	30	40	60	40	60
9	30	30	40	60	40	60	40
10	30	30	40	60	40	40	60
11	30	30	40	40	60	60	40
12	30	30	40	40	60	40	60

Since cost parameters do not change within each configuration, the minimum total cost value is the same for all solutions (140,972). The minimum cost solution includes manufacturers N3, N6, N8, N9, N10 and N12. The maximum reliability solution varies within each configuration, between 1,429and 1,477. The maximum total reliability network structure is also the same for all configurations and includes manufacturers N1, N6, N7, N9 and N12. Finally, we have presented a balanced solution, where we take equal objective weights. It is important to notice that in the "balanced solution", the network configurations change for different criteria weights. While configuration 1 includes manufacturers N1, N6, N7, N8, N9, N10 and N12; configuration 2 excludes N8 and includes N2. By running the model with different criteria weights, it is possible to directly reflect decision maker priorities into the operational network structure. We believe this DSS allows the decision makers to better understand and assess the effects of their choices over the network structure.

Table 30 DSS Solutions

	SOLUTIONS				Balanced Solution		
Solution	Minimum Cost	Network Configuration	Maximum Reliability	Network Configuration2	Total Cost	Total Reliability	Network Configuration3
1	140972	N3,N6,N8,N9,N10,N12	1443.75	N1,N6,N7,N9,N12	150090	1364	N1,N6,N7,N8,N9,N10,N12
2	140972	N3,N6,N8,N9,N10,N12	1466.68	N1,N6,N7,N9,N12	150650	1413	N1,N2,N6,N7,N9,N10,N12
3	140972	N3,N6,N8,N9,N10,N12	1429.12	N1,N6,N7,N9,N12	150090	1346.2	N1,N6,N7,N8,N9,N10,N12
4	140972	N3,N6,N8,N9,N10,N12	1452.24	N1,N6,N7,N9,N12	150650	1396.2	N1,N2,N6,N7,N9,N10,N12
5	140972	N3,N6,N8,N9,N10,N12	1443.66	N1,N6,N7,N9,N12	150090	1362.8	N1,N6,N7,N8,N9,N10,N12
6	140972	N3,N6,N8,N9,N10,N12	1466.71	N1,N6,N7,N9,N12	150650	1411.5	N1,N2,N6,N7,N9,N10,N12
7	140972	N3,N6,N8,N9,N10,N12	1438.75	N1,N6,N7,N9,N12	150090	1354.7	N1,N6,N7,N8,N9,N10,N12
8	140972	N3,N6,N8,N9,N10,N12	1462.09	N1,N6,N7,N9,N12	150650	1404.3	N1,N2,N6,N7,N9,N10,N12
9	140972	N3,N6,N8,N9,N10,N12	1453.82	N1,N6,N7,N9,N12	150090	1373.3	N1,N6,N7,N8,N9,N10,N12
10	140972	N3,N6,N8,N9,N10,N12	1477.03	N1,N6,N7,N9,N12	150650	1422.1	N1,N2,N6,N7,N9,N10,N12
11	140972	N3,N6,N8,N9,N10,N12	1448.91	N1,N6,N7,N9,N12	150090	1365.1	N1,N6,N7,N8,N9,N10,N12
12	140972	N3,N6,N8,N9,N10,N12	1472.41	N1,N6,N7,N9,N12	150650	1414.8	N1,N2,N6,N7,N9,N10,N12

4.6. CONCLUSIONS

In this chapter, we have presented a three stage approach to support the formation and operational planning of DMNs. The developed methodology involves a TOPSIS MCDM component, a Fuzzy inference system and a multi-objective MILP model. TOPSIS is used to compute the manufacturer reliability, the order criticality, and the customer priority indexes. Then, a fuzzy inference system is utilized to transform these indexes into an order priority index. Finally, a multi-objective model minimizes the cost and maximizes the order priority-weighted manufacturer reliability.

The main contribution of this work is the integration of customer, manufacturer and order data, for supporting network formation and operational planning processes. Even though DMNs are short term agile networks (formed to satisfy specific customer orders), customer and order characteristics are often neglected in DMN formation. By integrating these data, it is possible to learn from past manufacturer and customer performance, and design a network where orders are planned according to their priorities. The developed approach supports these decisions, by prioritizing customers, and by measuring criticality and priority of orders. On the other hand, by integrating manufacturer characteristics through a manufacturer reliability index, it will be possible to consider the past performances of manufacturers in network formation. Finally in the multi-objective model, DMNs are formed aiming at assigning more reliable manufacturers to more prioritized orders.

CHAPTER 5: FLEXIBILITY BASED OPERATIONAL PLANNING IN DYNAMIC MANUFACTURING NETWORKS

The Dynamic Manufacturing Network (DMN) is a new collaborative business model that relies on real time information sharing, synchronized planning and common business processes. Being the manufacturing industry application of the Virtual Enterprise (VE) concept, DMNs are operational networks formed among autonomous and globally dispersed partners. Despite their numerous practical benefits, such as optimized processes and access to new and global markets, they are particularly vulnerable to disruptions in their operations. A disruption that occurs in manufacturing or transportation of products may result in failed orders, thus decreasing whole DMN reliability.

As an alternative to the tendency of developing stochastic models to deal with uncertainty, we have focused on integrating flexibility into operational planning. (Tomasgard and Schutz, 2011) *proved that when an appropriate amount of flexibility is integrated in a supply chain, a deterministic approach may lead to equally good or better results than a stochastic model. Time, quality, flexibility and cost are the main DMN formation drivers* (Papakostas *et al.*, 2014)*. In this work we have proposed a multi-objective MILP model that simultaneously maximizes operational reactive flexibility, while minimizing total production, transportation, holding and network formation costs.*

5.1. INTRODUCTION

In this era of global competition, decreased profit margins and market turbulence, traditional supply chains are being transformed into more dynamic and adaptive network structures. A supply chain is defined as a system of autonomous companies that are linked by material and information flows, with the objective of delivering the right amount of product, to the right place with the right quality (Piramuthu, 2005; Wang, 2008). The agile manufacturing paradigm is a major driver in this shift, with its capability of continuously adapting to industrial requirements through short term operational supply chains (Pan and Nagi, 2013). These short term networks are known as Virtual Enterprises (VE), Virtual Organizations (VO), Dynamic Virtual Organizations (DVO), etc. (Camarinha-Matos, 2009). Within this new paradigm, the Dynamic Manufacturing Network (DMN) concept has emerged as a manufacturing industry application of VEs that rely on common business processes, real time (or close to real time) information sharing, centralized decision making and optimized operational planning (Viswanadham and Gaonkar, 2003; Papakostas *et al.*, 2014).

DMN formation and operational planning is not a one-time strategic problem, but an operational decision that needs to repetitively be taken according to partner requirements (capacities, competencies) and demand characteristics (buyer location and expected lead time) (Oh, Ryu and Jung, 2013). A DMN aims to select the optimal network configuration that has minimum total cost and satisfies on time delivery requirements (Wadhwa, Saxena and Chan, 2008). Since DMNs are formed through a group of geographically dispersed partners (mainly SMEs), available capacities and transportation modes also directly affect the DMN structure.

Despite their numerous benefits, such as time savings, cost reduction and visibility, DMNs are hard to plan and vulnerable in their operations (Li and Liao, 2007; Markaki, Kokkinakos, *et al.*, 2013). Due to the autonomy of partners, a DMN lacks control in its internal operations, and faces risks in its operations. Moreover, due to the globally dispersed structure of DMN partners, disruptions can occur during transportation or as a result of international restrictions (Singh *et al.*, 2011). For DMNs, reliability is a major performance criterion that cannot be compromised (Markaki, Kokkinakos, *et al.*, 2013). For DMNs where customer communication occurs through electronic marketplaces, a failed order not only means a lost order and low profit, but also possibly lost future demand. Additional performance measures are required in order to avoid any delay in promised customer delivery time, so that a high reliability can be maintained. A DMN needs to make sure the right customer receives the right amount of product, at the right time, with the right quality.

Supply chain flexibility is a strategy that is utilized to deal with potential risks and disruptions (Esmaeilikia *et al.*, 2014b). Contrary to other supply chain planning criteria such as cost, lead time, quality, flexibility does not represent a fixed performance, but a potential to deal with risks of unknown probability (Calvo, Domingo and Sebastián, 2008; Wang, 2008). In manufacturing context, it can be viewed as the capability of a manufacturing system to deal with both internal and external disruptions, while maintaining the competency and profitability levels (Gong, 2008). Maximizing flexibility while minimizing costs is one of the main challenges of supply chain planning (Wadhwa, Saxena and Chan, 2008; Singh *et al.*, 2011).

Integrating flexibility into DMN planning has the potential to improve network performance drastically (Wadhwa, Saxena and Chan, 2008). While several research works have contributed to supply chain flexibility at the strategical and tactical levels, the literature is still poor in research that considers flexibility as a dynamic capacity at the operational level. In this dissertation, we propose a methodology to support DMN formation and operational planning, with flexibility concerns. Initially we have reviewed the literature on the DMN context and existing short term supply chain planning models. Later, we have investigated the supply chain flexibility literature, and presented a new framework for flexibility. Finally, we proposed a multi objective Mixed Integer Linear Programming model to increase operational flexibility of DMNs through reactive flexibility measures.

5.2. THEORETICAL FOUNDATION AND LITERATURE REVIEW

Here we present a review of some related literature streams: context of the research and DMNs, planning in short term supply chains, and flexibility concerns in DMNs. Initially, a picture of the context is given by explaining the DMN business model and planning requirements. Later, we present a review of models developed to support operational planning in networked manufacturing. Finally we investigate the literature on supply chain flexibility, and present a new flexibility framework.

5.2.1. CONTEXT

Collaboration and information sharing radically shifted the industrial dynamics. New business models emerged within the Collaborative Networked Manufacturing paradigm, that require innovative strategies, governance principles and common processes to support their operations (Camarinha-Matos *et al.*, 2009). SMEs are particularly vulnerable in current market conditions, and their survival mainly depends on participating in these networks through pooling resources and sharing risks. The Virtual Enterprise concept arose within these trends to boost network agility (Pan and Nagi, 2010). A Virtual Enterprise is a short term, demand-driven, opportunity-specific network which is dissolved once the customer is served (Pan and Nagi, 2013). E-market places and ICT technologies facilitate the dynamic formation of Virtual Enterprises, by supporting secure and real time information sharing (Viswanadham and Gaonkar, 2003).

Dynamic Manufacturing Networks (DMN) are Virtual Enterprises that operate in manufacturing industries and rely on real time information sharing and optimized planning (Viswanadham and Gaonkar, 2003; Piramuthu, 2005). The coordinator/decision maker of a DMN can either be an OEM or a consortium of partners (Viswanadham and Gaonkar, 2003). A typical DMN, being a Virtual Enterprise, goes through a life cycle that is composed of creation, operation, evolution and dissolution stages (Wu and Su, 2005). In the creation stage of a DMN, a business opportunity is received via the e-marketplace. Then the DMN formation and planning "module" gets triggered in order to use and analyze real time partner capacity and cost data, so that an optimized DMN can be created. After the network is formed and the demand is confirmed, the DMN goes through its operation stage. In the operation stage, the DMN monitoring "module" tracks the execution of the initial plan with the aim of detecting disruptions and taking actions if needed (Kokkinakos *et al.*, 2013).

Being globally dispersed supply chains composed of autonomous partners, DMNs face operational risks on a daily basis (Papakostas *et al.*, 2012). In the execution phase, in case there is a disruption from the original plan, the common ICT platform takes the actions necessary to maintain on time delivery (Papakostas *et al.*, 2014). These actions are considered as a part of the "evolution stage" that involves changing the production plan and switching partners or transportation modes, to be sure the right product is delivered with the right quantity and quality at the right time. Once the demand is met, the DMN dissolves.

Several DMNs can be formed and operated simultaneously via an e-marketplace. In the long run, this business model also requires decision support tools for its other functions, such as performance evaluation, cost and benefit sharing, partner association/dissociation decision making, order promising, etc. (Viswanadham and Gaonkar, 2003). In order to form and operate DMNs, potential partners need to form a strategic partnership, an SME Network, so that DMN prerequisites as transparency, security, trust and interoperability are met (Papakostas *et al.*, 2014). These prerequisites allow the ICT-based business model to materialize and operate. Problems of trust between parties of a DMN may limit the willingness of partners to share information (Wu and Su, 2005) highlight the importance of information sharing in Virtual Enterprises. Especially in the DMN context, integrated decision making with effective decision synchronization becomes vital (Wadhwa, Saxena and Chan, 2008).

(Markaki, Kokkinakos, *et al.*, 2013) listed potential risks in DMN operation, such as, partner vulnerability due to information security issues, poor configuration of the network due to incorrect data, DMN dissolution if a key partner drops out, resistance to change, or loss of network reputation in case a partner fails. Thus it is beneficial to create strategies to deal with these or other possible disruptions.

In this dissertation we aim to contribute for improving the formation and operational planning stage of a DMN life cycle. Since the literature on DMN is rather limited, in the next section we review operational planning models developed for short term supply chains.

5.2.2. Planning in Short Term Supply Chains

Generally, recent articles in operational supply chain and agile manufacturing networks cover the formation and the planning of goal oriented dynamic networks rather than the case of "fixed" strategic supply chains. Naturally, cost minimization is the main planning driver in these networks, as in fixed supply chain planning. Transportation costs, modes and lead times are specifically important in these networks due to the geographically dispersed nature of manufacturers and customers. (Viswanadham and Gaonkar, 2003) have shown that the DMN structure is directly affected by buyer location.

Several researchers have also argued that it is too risky to depend on real time detailed information sharing, and therefore proposed distributed, agent-based models for network planning (Chan and Chan, 2010). These models highlight the decentralized nature of the partners by providing them with autonomy, while supporting their common interactions. Since the DMN business model relies on centralized processes and online information sharing, we omit this line of research. Interested readers may check (Lee and Kim, 2008; Kumar and Srinivasan, 2010) for a deeper understanding of this research stream.

Mathematical programming is the most popular approach for supply chain formation and planning. Through time, proposed models have evolved from Integer Programming models for partner selection, to complex MILP/MINLP models for lot sizing in production, transportation, and inventory levels of partners.

(Wu and Su, 2005) modeled the Virtual Enterprise partner selection problem with an Integer Programming formulation, with the minimum cost objective. The model is solved by a 2-phase heuristic, and tested with a case study from the mold manufacturing. (Viswanadham and Gaonkar, 2003) proposed a MILP model for profit maximization in the formation and operational synchronization of a four-stage internet-enabled dynamic manufacturing network. With the suggested model, the authors explored the variability of solutions with respect to different buyer locations, different order patterns, and the utilization of transshipment hubs. (Yimer and Demirli, 2010) developed a two phase MILP model to schedule dynamic supply chains with minimum cost, and solved the problem with genetic algorithms. (Chauhan *et al.*, 2006) developed a MILP model and a solution algorithm based on path relaxation heuristic, to form and plan an opportunistic supply chain with minimum cost. (Pan and Nagi, 2013) extended this work by allowing the selection of multiple partners in each supply chain echelon, and proposed a lagrangian heuristic to solve the problem. (Singh *et al.*, 2011) consider a multi stage global supply chain network problem with a set of risk factors (such as late shipment, exchange rates, quality problems, logistics and transportation breakdowns, and production risks), their expected values and probability of occurrence. The authors embedded these risks in a cost function, and solved the problem to minimize total cost.

More recently, some authors have been developing robust formulations to integrate uncertainty on cost, lead time, demand and supply in supply chain planning decisions. (Pan and Nagi, 2010) built a robust MILP model to support supply chain design in agile manufacturing, under uncertain demand. The authors solved the model with a new heuristic based on K shortest path algorithm. (Babazadeh and Razmi, 2012) also built a robust stochastic model for a new business opportunity, with uncertain demand and cost. (Lalmazloumian *et al.*, 2013) considered robust planning of an agile manufacturing network in a build-to-order environment. The MILP model aims to minimize total supply chain cost under demand and cost uncertainty, and is applied in computer accessories manufacturing.

Fuzzy set theory is also used to integrate uncertainty to the mathematical models. (Demirli and Yimer, 2008) developed a Fuzzy MILP model to support scheduling in a BTO environment. The authors have utilized fuzzy numbers to represent uncertainties in various operational cost parameters, and have tested the model with a case study in the furniture supply chain.

(Zhang, Luo and Huang, 2012) explored the integration of real life parameters in network planning, within a dispersed manufacturing context. The developed bi-objective model integrates currency exchange rates and export VAT rates, while simultaneously minimizing weighted activity days and total supply chain costs. The model is tested with a case study in the footwear industry. Another multi-objective model is developed by (Dotoli, Fanti and Mangini, 2007) that considers total cost, energy and CO2 emissions criteria, to configure integrated e-supply chains. They also proposed two multi-criteria optimization techniques (Fuzzy AHP and Fuzzy TOPSIS) to rank pareto optimal solutions, and presented a case study in the desktop computer system industry.

Apart from optimization techniques, several researchers have also proposed application of other types of methodologies to support decision making. (Piramuthu, 2005) developed a knowledge based framework for automated dynamic supply chain configuration,, a machine learning approach that explores how to assign the best nodes at each echelon of the network, for each combination of order attributes such as price, lead time and quantity. (Papakostas *et al.*, 2012) introduced a decision making approach that creates different DMN configurations, that are evaluated according to the average tardiness and the cost. (Papakostas *et al.*, 2014) proposed a utility function composed of cost, time and quality criteria, to evaluate and compare different DMN configurations, with an application in the furniture industry.

Contributing to supply chain-wide integration and optimization is surely a valuable approach to improve supply chain performance as a system, rather than focusing on each company separately. Several authors have focused on developing complex mathematical models that consider all operational costs through the network, reflecting uncertainties and risks, and proposed solution methods to solve in these models in acceptable short computational times.

However, during the literature review we haven't come across any study that considers reconfigurability and flexibility concerns in short term supply chain planning. Short lead times and complex processes make planning a critical issue in these supply chains. Unbalanced plans or deviations from plan in the execution process may easily lead to unmet demand or quality problems. As VEs, DMNs frequently change their plans and configuration, in case of disruptions. It is therefore important to integrate these reconfiguration and flexibility concerns in operational planning, to improve the adaptability of these networks to disruptions.

5.2.3. Flexibility Concerns in DMN Planning

In this section of the chapter we have investigated flexibility concerns in DMN planning. Initially we have presented several flexibility definitions and explore different perspectives. Consecutively, we have developed the supply chain loss prevention process and pointed out different stages and the associated strategies. Finally, we have identified a list of reactive flexibility strategies and presented relevant research.

5.2.3.1. Supply Chain Flexibility

Supply chain flexibility is the inherent capability of a system to deal with internal and external risks and disruptions (Gong, 2008; Esmaeilikia *et al.*, 2014b). The total flexibility of a supply chain is the combination of flexibilities at strategic, tactical and operational levels (Stevenson and Spring, 2007; Esmaeilikia *et al.*, 2014a) as well as flexibilities at basic, aggregate and system levels (Barad and Even Sapir, 2003). In the supply chain flexibility decision making process, the first step is to define the planning level to address so that we can study possible risks and disruptions to be mitigated (Esmaeilikia *et al.*, 2014b). This understanding will allow the decision maker to choose and integrate the key flexibility dimensions to the system, that target the most prominent risks (Tomasgard and Schutz, 2011; Simangunsong, Hendry and Stevenson, 2012; Esmaeilikia *et al.*, 2014b). In this study we will focus on flexibility in the operational level since DMNs are short term operational networks build to respond specific customer demand.

Since flexibility comes with a cost, not a fully flexible but a balanced design is required (Jain *et al.*, 2013). The effects of different flexibility levels in the supply chain operational performance is investigated by (Aprile, Garavelli and Giannoccaro, 2005). The authors pointed out that supply chain configurations with limited process and logistics flexibility often perform as good as other options providing total flexibility. Limited flexibility networks have less complexity and cost, and are often preferable

5.2.3.2. Supply Chain Loss Prevention Process

In order to explain how flexibility contributes to risk and disruption mitigation, we have explained supply chain loss process and possible strategies. The four stages of supply chain loss prevention process are: uncertainty, risk, disruption and loss. While uncertainty represents a positive or negative deviation in the data, risk is always on the negative side (Simangunsong, Hendry and Stevenson, 2012). In Figure 31 we present a new perspective to the supply chain loss prevention process, and the necessary strategies to mitigate the problems at each stage. When a decision maker has access to a probabilistic expression of the data or has an idea of the possible scenarios, more robust decisions can be taken. With a robust strategy, a supply chain can stay resilient within a predicted range of the data (Tomasgard and Schutz, 2011). However, once data is not fully predictable, flexibility strategies are to be applied.

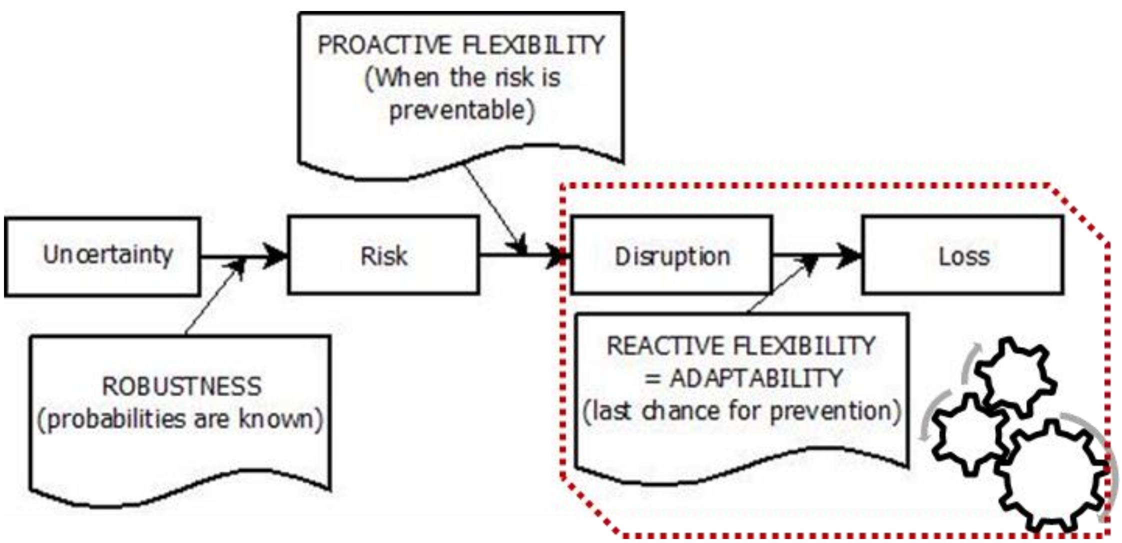

Figure 31 Supply chain loss prevention process

In terms of the way they approach risk mitigation, supply chain flexibility strategies can be classified as proactive and reactive (adaptive) flexibility. While proactive strategies are effective in mitigating internal risks, reactive strategies are utilized to deal with the consequences of disruptions (Stevenson and Spring, 2007).

Proactive flexibility strategy is applied to minimize disruption risk. We can classify the risks involved in DMN processes as: supply (behavioral autonomy) risk, production/distribution risk, external risks (international regulations, natural disasters, etc.), and ICT risks (Li and Liao, 2007; Tang and Tomlin, 2008; Singh *et al.*, 2011). Some examples of proactive flexibility strategies are collaboration, ICT system, postponement, risk pooling, strategic stock, flexible supply base, make and buy, economic supply incentives, flexible transportation and revenue management (Tang, 2006; Simangunsong, Hendry and Stevenson, 2012; Angkiriwang, Pujawan and Santosa, 2014) at the strategic level and volume flexibility, delivery flexibility, operational flexibility, sourcing flexibility, etc. (Esmaeilikia *et al.*, 2014b) at the tactical level. It should be noted that it is out of our intention to present here a full literature review of flexibility. Interested readers may benefit from (Simangunsong, Hendry and Stevenson, 2012; Esmaeilikia *et al.*, 2014b).

The last stage of the supply chain loss process is actual occurrence of a disruption. Once a disruption happens in a supply chain, it is required to react and deal with the consequences of the disruption.

5.2.3.3. Reactive Flexibility

Within the DMN context, we use the term disruption as the deviation from the initial plan, characterized by delays or failure. Disruptions in DMN context are identified as delayed demand, failed demand, half delivered demand or low quality demand. Since DMN does not have complete control over its partners, it is possible to observe disruptions in partners operations or transportations between partners. If these disruptions are not correctly mitigated, the business network may face short term and long term losses such as poor customer service, poor reliability, lost customers and ultimately low profits (Singh *et al.*, 2011; Markaki, Kokkinakos, *et al.*, 2013).

At this stage, reactive flexibility strategies are required to quickly reconfigure the supply chain, in order to compensate disruption and prevent loss. Reactive flexibility strategies (can also be viewed as a buffering strategies for the system) are listed in the literature as safety stock, capacity buffer, supplier backups and safety lead times (Angkiriwang, Pujawan and Santosa, 2014). In Figure 32 we have identified reactive flexibility strategies in DMN context as multiple suppliers, multiple transportation modes, slack capacity, slack lead time, passive capacity (the capacity of partners that can be included to the DMN if the current partners cannot respond to rescheduling needs) and slack transportation capacity.

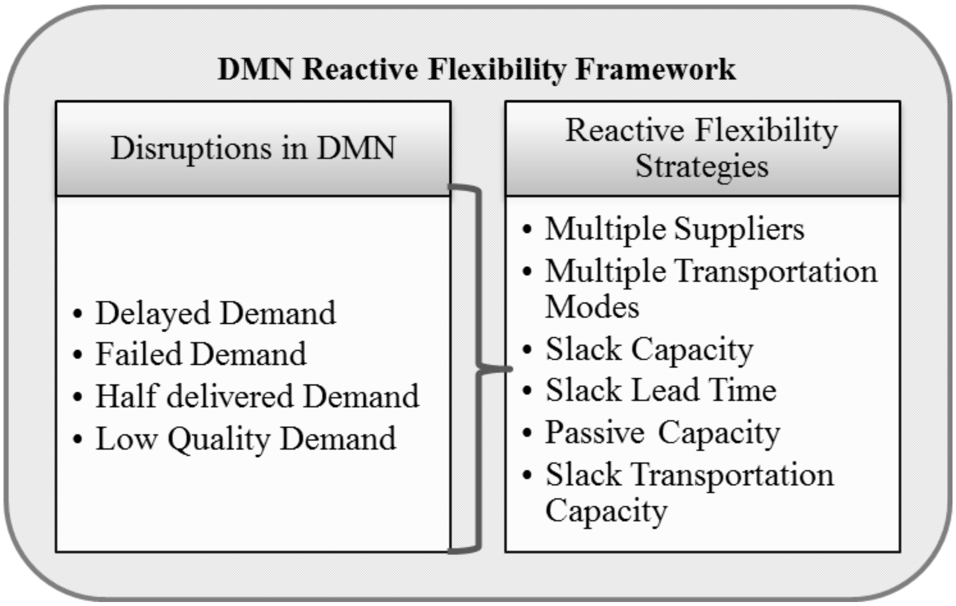

Figure 32 DMN Reactive Flexibility Framework

Reactive flexibility is also called as adaptability, and due to the scarcity of research under the name reactive flexibility; we have also investigated the relevant research under the name adaptability.

(Ivanov, Sokolov and Kaeschel, 2010) defined adaptability as “the capacity of a supply chain in -modifying its actions or in changing its structure in accordance with the alterations in environmental conditions”. The ultimate goal in introducing adaptability to the system is to support its performance such as demand fill rate, higher utility rate, better customer service (Chan and Chan, 2010). A different perspective in adaptability is “flexibility in decision making” where decision makers are allowed to change or make further decisions once the plan is in execution while keeping the promised service level (Barad and Even Sapir, 2003).

Flexibility and adaptability concerns have also been investigated in operational planning. (Wadhwa, Saxena and Chan, 2008) proposed a framework for flexibility in dynamic supply chain management. The model is tested for parameters such as demand pattern, lead time, ordering cost, inventory and transportation distance and flexibility is found to be decreasing with total supply chain costs. (Chan and Chan, 2010) used a simulation model to understand and compare the benefits of adaptability and flexibility in distributed manufacturing supply chains. They have found that adaptability significantly increases the demand fill rate, and both adaptability and flexibility decrease total system costs when compared to stochastic models.

(Ivanov, Sokolov and Kaeschel, 2010) present a multi structural framework for adaptive supply chain planning and operations control. Based on a broader conceptual framework, the authors developed mathematical models to support the planning, analysis, monitoring and reconfiguration stages of adaptive supply chains. (Ivanov, 2010) suggests an adaptive conceptual framework that assists, linking and aligning supply chain design and strategic, tactical and operational level decisions. The framework is composed of several model blocks and takes into account uncertainty and the interrelations of all management levels. (Shan *et al.*, 2013) developed a rapid response production system for aircraft manufacturing, which monitors operations, gets triggered with abnormal events, and follows business processes to solve and learn from the problems. (Oh, Ryu and Jung, 2013) developed a framework to support the reconfiguration of supply networks, based on flexibility strategies. This model is composed of supply network architecture, a suitability of the configuration (SOC) evaluation model, a goal model of the nodes, and a reconfiguration mechanism. When a goal of one manufacturing node changes, the reconfiguration process gets triggered.

A DMN tracks the operations of its members in the global supply chain, and reschedules orders by reconfiguring the network in terms of disruptions. The reliability of the network can be jeopardized by careless mistakes of one partner, and might be difficult to recover in the long run (Markaki, Kokkinakos, *et al.*, 2013). By integrating reactive flexibility strategies to the operational planning decision making, our objective is to increase the capability of DMN to react future disruptions and reschedule the failed orders in order to maintain on time delivery.

5.3. METHODOLOGY

To deal with integrated DMN formation and operational planning in discrete complex products manufacturing, we have developed a multi objective Mixed Integer Linear Programming (MILP) model that takes into account real time capabilities, costs and capacities of partners. This model aims to design the optimal DMN structure with a balanced solution between costs and flexibilities and to identify production, inventory and transportation lot sizes for the different partners. If any disruption is tracked in the process, the model is likely to propose a system with reconfiguration.

5.3.1. MILP MODEL FOR DMN FORMATION AND OPERATIONAL PLANNING

We have also here utilized the MILP model of Chapter 4. As explained in the third Section of Chapter 4. In that Chapther, the proposed model has an objective function that aims to minimize the total operational costs. In this work in order to create flexibility based operational plans, we have utilized both a cost minimization function, and the flexibility objectives explained below.

5.3.2. FLEXIBILITY IN PLANNING

Here, we present some flexibility measures for DMN operational plans that will be integrated, as objective functions, in the MILP model, to generate operational plans that are both flexible and cost efficient. We have identified two reactive flexibility measures: Slack Capacity and Slack Time. By integrating these two flexibility measures, we want to generate more flexible operational plans, by creating internal buffers for dealing with disruptions.

Flexibility in terms of slack time and cost are conflicting objectives since lot sizing models are designed to schedule forward, in order to prevent holding costs (under the assumption that production costs are equal in different time periods) and to include the cheapest partners. Figure 33 is a schematic representation of different operational plans, generated according to different objectives. While in a *minimum cost solution*, all production and transportation are scheduled forwards with no active slack time, in a *maximum Slack time flexibility solution,* all production and transportation operations are scheduled backwards with maximum active slack time. A *mixed solution of flexibility and cost* can be created through the objective function (with adequate weights for the criteria), in order to generate a balanced schedule, with active slack time and a reasonable cost.

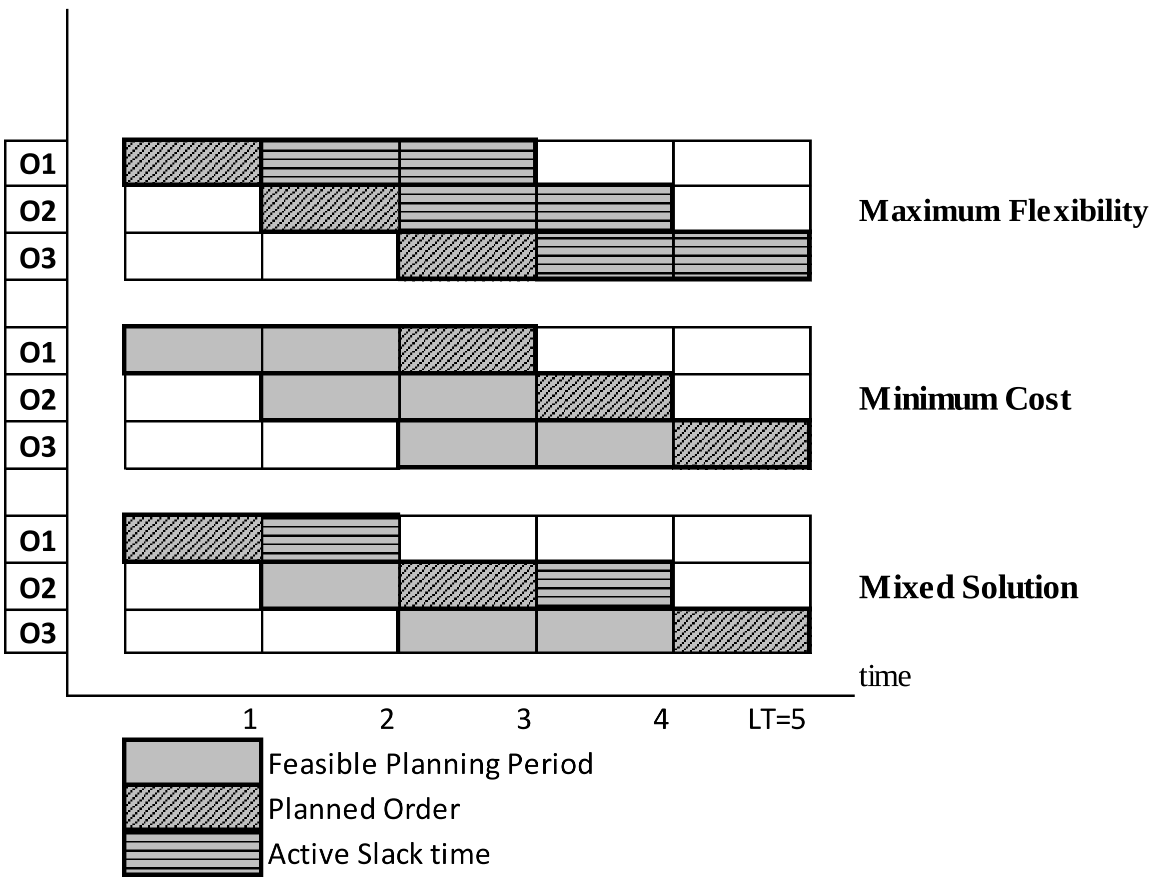

Figure 33 Plans with different objectives

We created two flexibility measures as follows.

Objective function 2: Total slack time maximization

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{k=1}^{K}\sum_{i=1}^{O}\frac{Z_{t,k,i,n}}{D_{k,c}}\times(LFT_{k,i}-t)\times(MPT_{k,i})$$

The first component of this function scales the production with the order size, aiming to decide what percentage of the customer order is going to be assigned. The second component calculates the active slack time by subtracting the scheduled time t from the latest production time of order k in operation i. The final component of the formula is the maximum production time, in order to measure at what point of the schedule, slack time is assigned. It is important to note that a slack time assigned at an earlier operation creates more schedule flexibility than assigning slack time to a later operation.

<u>Objective function 3: Total Slack Capacity maximization</u>

$$\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{O}\left(Cap_{tin} \times Y_{in} - \sum_{k=1}^{K} Z_{tkin} \times UPT_{kin}\right)$$

The first component of the function calculates the total capacity of all partners that are selected for the DMN. The second component subtracts the utilized capacity for production from the total selected capacity. These capacities are summed equation over all operations, all manufacturing partners, and all time periods.

5.4. ILLUSTRATIVE EXAMPLE

In order to provide an example for application of the proposed model, we have created a network, with five echelons and 12 manufacturing partners, as depicted in Figure 34. We have adapted the illustrative example values from data obtained by a real supply chain by creating data following the real, observed patterns. Table 31 has the characteristics of the created data. All data was created via uniform distribution, within a predefined interval. Apart from the demand, the rest of the utilized data is presented in Appendix 1.

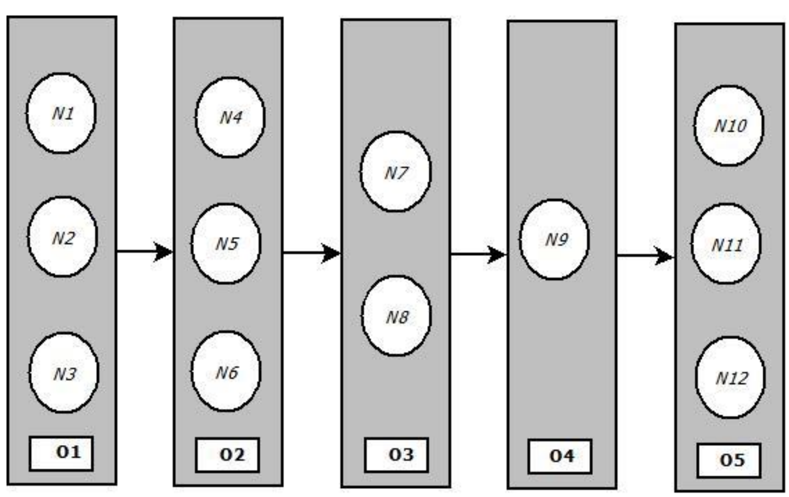

Figure 34 Network structure

Table 32 presents the generated demand data. The second column defines the operations sequence of each order through consecutive echelons. The third column shows the size of each order. The fourth column identifies the lead time of each order, and the final column presents the customer whom the order is processed for.

Table 31 Data characteristics

Data Definition	Data Structure
Selection Cost	Uniform(1000,4000)
Assignment Cost	Uniform (600,1000)
Fixed Production Cost	Uniform (40,80)
Unit Production Cost	Uniform (2,5)
Unit Production Time	Uniform (1,5)
Capacity	Uniform (3000,4000)
Fixed Transportation Cost	Uniform (100,200)
Unit Transportation Cost	Uniform (1,5)
Unit Weight	Uniform (2,8)
Unit Weight to Customer	Uniform (2,7)
Starting Inventory Holding Cost	Uniform (1,3)
Finishing Inventory Holding Cost	Uniform (3,5)
Transportation Capacity	Uniform (300000,700000)
Customer Transportation Capacity	Uniform (200000, 400000)
Customer Unit Transportation Cost	Uniform (3,9)

Table 33 shows the capacity data for each manufacturing unit, through different time periods. The capacity unit is “available processing time”. Note that processing time of each order varies between different manufacturers. This is due to the differences in labor requirements of each order and the technologic capabilities of the partner operations.

Table 32 Demand Data

Order	Operational Sequence	Demand	Lead Time	Customer
K1	O1,O2,O3,O4,O5	120	6	C1
K2	O1,O3,O4,O5	140	6	C2
K3	O1,O2,O4,O5	150	6	C4
K4	O1,O2,O5	100	6	C3
K5	O1,O2,O3,O5	120	6	C6
K6	O1,O2,O4,O5	110	6	C8
K7	O1,O2,O5	110	6	C7
K8	O1,O2,O5	130	6	C7
K9	O1,O2,O4,O5	140	6	C5
K10	O1,O2,O3,O5	150	6	C5

In order to provide tradeoffs solutions between cost and flexibility, we have computed the optimal values, with different objective weights. We have utilized weighted sum method for solving this multi objective model. The MILP model is solved by using the Cplex optimization software.

Table 33 Capacity data in terms of manufacturing partner and time period

	CAPACITY					
Partner	**t=1**	**t=2**	**t=3**	**t=4**	**t=5**	**t=6**
N1	3003	3559	3759	3990	3251	3080
N2	3654	3900	3106	3332	3129	3016
N3	3192	3126	3450	3919	3848	3147
N4	3664	3132	3689	3965	3479	3695
N5	3732	3271	3625	3092	3960	3505
N6	3885	3969	3737	3756	3148	3105
N7	3166	3997	3923	3315	3460	3828
N8	3566	3390	3039	3342	3309	3599
N9	3257	3404	3541	3403	3928	3500
N10	3327	3139	3516	3225	3765	3578
N11	3240	3772	3407	3982	3808	3369
N12	3807	3237	3694	3049	3489	3441

Table 34, Table 35, Table 36 and From these tables, we can see that, as the weight of total cost increase, the total slack time and the total slack capacity values for the same slack capacity and slack time weights tend to decrease. Thus, providing flexibility in the network requires adding slack capacity and slack time and comes with a cost.

Table 37 present the optimal total Cost, total slack time and total slack capacity values and the associated network configurations for different objective function weights. As shown in Table 34, we have run the model by using 0.2 as cost weight and 0.8 as flexibility weight. In Table 35, we present the solutions that were found by running the model with 0.4 cost and 0.6 flexibility weight. On the other hand, in Table 36 the weight for total cost objective is taken as 0.6 and the weight for total flexibility objective is taken as 0.4. Finally, in From these tables, we can see that, as the weight of total cost increase, the total slack time and the total slack capacity values for the same slack capacity and slack time weights tend to decrease. Thus, providing flexibility in the network requires adding slack capacity and slack time and comes with a cost.

Table 37 we present the solutions we have achieved by taking cost weight as 0.8 and flexibility weight as 0.2.

Note that in the weighted sum method objective values sum up to one. Therefore, when the weight of total cost is taken as 0.2, the weight of total flexibility is taken as 0.8 and when the weight of total cost is taken as 0.4, the weight of total flexibility is taken as 0.6.

Table 34 Tradeoffs between Slack Lead Time and Slack Capacity Solutions for Cost Weight 0.2

W COST=0.2, W FLEX=0.8					
W ST	W SC	Total Cost	Total Sl Time	Total Sl Capacity	Network Configuration
0	1	171570	12	239250	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.1	0.9	177090	174	239250	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.2	0.8	179710	183	239250	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.3	0.7	181540	187	239250	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.4	0.6	182740	189	239250	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.5	0.5	182610	189	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.6	0.4	182610	189	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.7	0.3	182610	189	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.8	0.2	182490	189	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.9	0.1	182490	189	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
1	0	178140	189	132080	N1,N3,N6,N8,N9,N10,N12

The first two columns of Table 34, Table 35, Table 36 and From these tables, we can see that, as the weight of total cost increase, the total slack time and the total slack capacity values for the same slack capacity and slack time weights tend to decrease. Thus, providing flexibility in the network requires adding slack capacity and slack time and comes with a cost.

Table 37 stand for criteria weights used for Slack Time and Slack Capacity. The maximum cost value for the illustrative example is calculated as 250,000, while minimum cost value is 165,652. On the other hand, the maximum and minimum capacity values are 240,852 and 87,846. Finally, the maximum slack time scenario objective (where all orders are scheduled backwards) has a value of 189, while minimum slack time scenario objective (with forward scheduling) is 0. Slack capacity and slack lead time are elements of flexibility and the weight they separately take in the objective function is proportional to the weight given to flexibility. For instance, when the weight of flexibility is 0.4 and the weight of slack time is 0.4; the weight of slack time in the objective functions is the multiplication of 0.4 with 0.4 which is equal to 0.16. Thus, in the same example the weight of cost is 0.6, the weight of slack time is 0.16 and the weight of slack capacity is (0.4*0.6) 0.24.

Table 35 Tradeoffs between Slack Lead Time and Slack Capacity Solutions for Cost Weight 0.4

W COST=0.4, W FLEX=0.6					
W ST	W SC	Total Cost	Total Sl Time	Total Sl Capacity	Network Configuration
0	1	170750	8	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.1	0.9	174580	153	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.2	0.8	176970	174	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.3	0.7	176970	174	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.4	0.6	176970	174	239090	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.5	0.5	179470	183	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.6	0.4	179470	183	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.7	0.3	180330	185	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.8	0.2	181290	187	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.9	0.1	182490	189	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
1	0	178140	189	132080	N1,N3,N6,N8,N9,N10,N12

Table 36 Tradeoffs between Slack Lead Time and Slack Capacity Solutions for Cost Weights 0.6

W COST=0.6, W FLEX=0.4					
W ST	W SC	Total Cost	Total Sl Time	Total Sl Capacity	Network Configuration
0	1	170750	8	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.1	0.9	172510	99	238700	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.2	0.8	174580	153	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.3	0.7	175240	162	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.4	0.6	175240	162	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.5	0.5	176530	172	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.6	0.4	176850	174	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.7	0.3	176850	174	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.8	0.2	176850	174	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.9	0.1	174280	174	196460	N1,N3,N4,N5,N6,N7,N8,N9,N10,N12
1	0	174350	180	132080	N1,N3,N6,N8,N9,N10,N12

From these tables, we can see that, as the weight of total cost increase, the total slack time and the total slack capacity values for the same slack capacity and slack time weights tend to decrease. Thus, providing flexibility in the network requires adding slack capacity and slack time and comes with a cost.

Table 37 Tradeoffs between Slack Lead Time and Slack Capacity Solutions for Cost Weights 0.8

W COST=0.8, W FLEX=0.2					
W ST	W SC	Total Cost	Total Sl Time	Total Sl Capacity	Network Configuration
0	1	170750	8	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.1	0.9	170750	8	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.2	0.8	171380	53	238810	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.3	0.7	171230	123	218190	N1,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.4	0.6	172140	146	218190	N1,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.5	0.5	172140	146	218190	N1,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.6	0.4	172140	146	218190	N1,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
0.7	0.3	171740	155	196610	N1,N3,N4,N5,N6,N7,N8,N9,N10,N12
0.8	0.2	170160	152	153830	N1,N3,N6,N7,N8,N9,N10,N12
0.9	0.1	171240	163.2	153830	N1,N3,N6,N7,N8,N9,N10,N12
1	0	171040	163.2	131780	N1,N3,N6,N8,N9,N10,N12

Moreover, we have also found out that the cost of unit slack time tends to decrease as the weight of total slack time increases in the total flexibility objective. Accordingly, also as the weight of total slack capacity decrease in the flexibility objective, the cost of unit slack capacity also increases. Figure 35 denotes slack capacity and slack lead time tradeoff for different total cost weights in the objective function.

As seen from Figure 35 low cost weights provide highly flexible network configurations. However, as denoted in the tables, the total costs of the plans created through small low weights are higher than the plans created through higher cost weights. While taking cost weight as 0,2 provides full slack capacity in the network, the associated costs are highest. The tradeoff between slack time and slack capacity becomes more apparent as the weight of cost increase and weight of flexibility increase. The objective of the decision making process is to come up with a solution with not only high flexibility values, both in terms of slack capacity and slack time; but also fairly low values in terms of cost. Because of this concern, it is advised to create candidate DMN configurations through utilizing cost weights that are higher than flexibility weight.

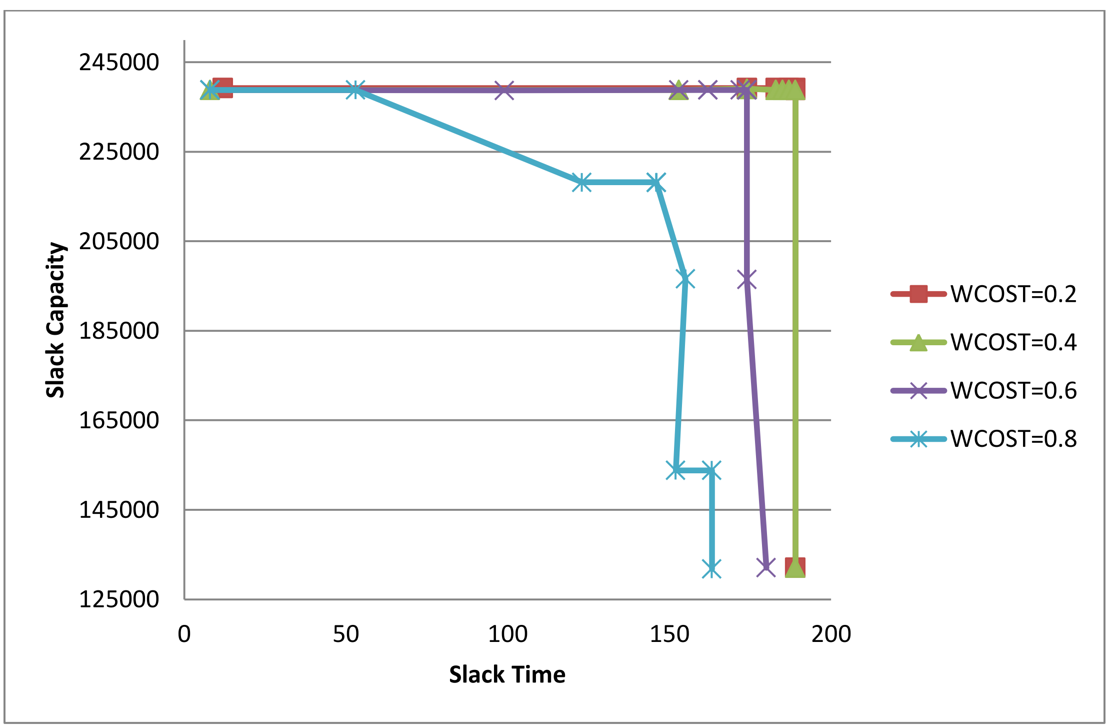

Figure 35 Slack Time Slack Capacity tradeoff for different cost weights

Slack capacity values change according to the network configuration and production lot assignment. On the other hand, slack lead time relates to backward or forward scheduling of the production plan. By presenting DMNs with both slack lead time and slack capacity, it will be possible to increase the likelihood of rescheduling in case of a disruption.

5.5. SCENARIO ANALYSIS

DMNs are order driven networks, mainly pushed by demand. Moreover, partner selection cost, as a fixed cost added to the Network formation cost once a partner is included to the network, is also an uncertainty factor that is potent in DMN structure. Partner selection cost is related with inter-organizational communication, supportive managerial activities and agreement procedures. Moreover, the cost of analyzing the production processes of an order and the cost of changes required in the production processes are also involved in the partner selection cost. Even though partner selection costs are much higher in other business models where a Strategic Partnership and an ICT system do not enable the communication and orchestration between partners, in DMN Design this cost is still significant.

In order to understand how the multi objective MILP model functions under different demand and partner selection cost structures, 9 scenarios were created with different demand and partner selection cost values. We have defined three different demand structures as: low demand, medium demand, and high demand. On the other hand, partner selection cost scenarios were also identified as low partner selection cost, medium partner selection cost and high partner selection cost.

This led us to generate and analyze nine different scenarios, for all the combinations of partner selection cost with demand.

Table 38 presents the order lot sizes for different demand scenarios. We have created three demand scenarios with different demand values for each order. The network aims to satisfy 10 orders that are composed of different operational sequences as shown in the table. It is likely for an SME Network to receive demand that is much lower than its overall capacity. It is important to note that, SME Network is an alliance of autonomous companies and not all of them have to be involved in each DMN.

Table 38 Order Sizes for different Demand Scenarios

Order	Low Demand	Normal Demand	High Demand	Operational Sequence
K1	110	220	330	O1,O2,O3,O4,O5
K2	110	220	330	O1,O3,O4,O5
K3	120	240	360	O1,O2,O4,O5
K4	120	240	360	O1,O2,O5
K5	80	160	240	O1,O2,O3,O5
K6	80	160	240	O1,O2,O4,O5
K7	120	240	360	O1,O2,O5
K8	120	240	360	O1,O2,O5
K9	100	200	300	O1,O2,O4,O5
K10	100	200	300	O1,O2,O3,O5

Table 39 presents partner selection costs for all the three cost scenarios. In this study, it was assumed that the SME Network is composed of 12 partners all of whom have different capacities, processing times and capabilities. The capacity of each SME Network partner is denoted in terms of total processing times. On the other hand, manufacturing time required for each order also varies in different partners. Therefore, when the orders are assigned to different partners, the final total slack capacity value alters.

Table 39 Partner Selection Costs for all Scenarios

Partner	Low Partner Selection Cost	Medium Partner Selection Cost	High Partner Selection Cost
N1	545	1090	2180
N2	1755	3510	7020
N3	1220	2440	4880
N4	1370	2740	5480
N5	510	1020	2040
N6	1835	3670	7340
N7	1015	2030	4060
N8	1200	2400	4800
N9	1740	3480	6960
N10	1715	3430	6860
N11	1400	2800	5600
N12	1765	3530	7060

5.5.1. *SOLUTIONS*

All of the nine scenarios are run with the same cost and flexibility weights, by only changing slack capacity and slack time weights. The chosen weights for flexibility and cost are weight of flexibility=0.3 and weight of cost=0.7. These values are chosen in order to find satisfactory trade-off solutions and to see how optimal slack capacity and slack lead time values change with respect to different weights. Given the fact that a highly flexible or fully flexible network comes with a proportionally higher cost which is less likely to be accepted by the decision makers; we have utilized lower flexibility weight (0.3) and higher cost weight (0.7).

Table 40 Total Cost Values for 9 Scenarios

WTIME	LD-LSC	LD-MSC	LD-HSC	MD-LSC	MD-MSC	MD-HSC	HD-LSC	HD-MSC	HD-HSC
0	134,940	148,740	169,910	216,580	232,650	260,720	299,850	315,920	348,060
0.1	134,980	148,740	167,150	216,580	232,650	260,720	299,850	315,920	348,510
0.2	135,340	149,110	167,710	217,570	233,640	261,460	301,170	317,240	349,380
0.3	135,340	147,750	169,640	217,570	233,750	262,310	303,640	319,710	351,850
0.4	136,230	149,390	168,340	220,380	236,450	262,070	304,610	320,680	352,820
0.5	137,340	149,800	168,670	221,140	237,210	262,070	305,587	321,940	354,080
0.6	137,340	149,350	167,300	221,140	237,870	262,240	306,950	323,020	355,160
0.7	137,700	149,060	167,300	222,520	238,590	260,950	307,940	324,010	356,150
0.8	137,590	148,740	167,300	223,180	239,250	260,060	307,940	324,010	356,150
0.9	137,590	148,350	167,300	223,180	239,250	260,130	307,940	324,010	356,330
1	137,570	148,350	168,150	223,180	238,990	258,290	309,740	325,810	356,520
Minimum Cost	134,187	145,032	163,982	216,578	231,824	253,136	299,853	315,923	344,123
Maximum Cost	161,000	177,000	209,000	269,000	286,000	318,000	392,000	408,000	440,000

Table 40, Table 41 and Table 42 presents the optimal values for the total cost, total slack time and total slack capacity objective functions. Table 40 presents the optimal total cost values found in the 9 scenarios. Note that, since demand and partner selections costs are different in each scenario, , the computed minimum total cost value for each scenario is also different. Table 40 also contains the associated minimum cost values below each column. For instance, while the minimum total cost is found as 134,187 for “low demand and low selection cost” scenario, it is computed as 253,136 for “medium demand and high selection cost” scenario. On the other hand, the first column on the left stands for the weight that was used for slack time. Note that, in the weighted sum method, slack time and slack capacity weights sum up to 1. Therefore when slack time weight is 0.2, slack capacity weight is 0.8. By changing the values of slack time and slack capacity weights, our intention is to find candidate solutions that are flexible both in terms of capacity and time.

Table 41 presents the total slack time values computed for different combinations of slack time and slack capacity weights for all of the nine scenarios. Note that, for the first six scenarios, the maximum total slack time is found as 189 and the minimum total slack time is found as 0. On the other hand, for the high demand scenarios, the maximum slack time is computed as 187.808 and the minimum slack time is computed as 5.275. The differences in minimum and maximum slack times occur due to capacity restraints. Hence, a plan with a higher total slack time value is more backwards scheduled and the associated network has more time to mitigate a disruption. Obviously, when we increase the weight of total slack time in the objective function, we create solutions higher total slack time values. However, the plan we are looking for has to be flexible both in terms of slack time and slack capacity.

Table 41 Total Slack Time Values for the 9 Scenarios

WTIME	LD-LC	LD-MC	LD-HC	MD-LC	MD-MC	MD-HC	HD-LC	HD-MC	HD-HC
0	8	12	9	0	0	9	9.76	9.47	9.47
0.1	17	12	18	0	0	9	9.76	9.47	33
0.2	53	48	61	50	50	45	60	60	60
0.3	53	56	137	50	53	66	102	102	102
0.4	99	123	146	113	113	111	116	116	116
0.5	137	137	153	128	128	111	128	128	128
0.6	137	146	152	128	137	134.45	137	137	137
0.7	146	153	152	146	146	134.45	144	144	144
0.8	153	155	152	153	153	134.45	144	144	144
0.9	153	152	152	153	153	135	144	144	156
1	155	152	161	153	153	124	153	153	156.85
Min Time	0	0	0	0	0	0	5.275	5.275	5.275
Max Time	189	189	189	189	189	189	187.808	187.808	187.808

Table 42 presents the optimal total slack capacity values computed by giving different slack capacity and slack time weights to all of the nine scenarios. As shown in the rows below the table, scenarios with the same demand values (such as Low Demand and Low Selection Cost and Low Demand and Medium Selection cost), have equal maximum total capacity values.

On the other hand, since the SME Network total capacity is fixed, when we assign more demand to the network, the maximum slack capacity value decreases. As seen from Table 42, while maximum slack capacity values for the low demand scenarios are 242,902, for high demand scenarios they are found as 225,342. The slack capacity values seem very high because they represent the summation of all slack capacity values through all selected partners for all times. Slack capacity values provide a measure of total slack capacity in the network it will be possible to compare so different network configurations for the same scenarios.

Table 42 Total Capacity Values for the 9 Scenarios

WTIME	LD-LC	LD-MC	LD-HC	MD-LC	MD-MC	MD-HC	HD-LC	HD-MC	HD-HC
0	241,310	220,720	177,270	230,940	230,940	209,890	220,810	220,810	220,810
0.1	241,310	220,720	155,340	230,940	230,940	209,890	220,810	220,810	220,570
0.2	241,310	220,720	155,340	230,940	230,940	209,890	220,570	220,570	220,570
0.3	241,310	199,140	155,340	230,940	230,940	209,880	220,810	220,810	220,810
0.4	241,230	199,140	134,400	230,940	230,940	188,310	220,810	220,810	220,810
0.5	241,310	199,140	134,400	230,940	230,940	188,310	220,810	220,810	220,810
0.6	241,310	177,210	113,160	230,940	231,110	166,140	220,810	220,810	220,810
0.7	241,310	156,140	113,160	231,100	231,110	145,190	220,810	220,810	220,810
0.8	220,720	134,400	113,160	231,110	231,110	123,330	220,810	220,810	220,810
0.9	220,720	113,160	113,160	231,110	231,110	123,330	220,810	220,810	155,520
1	178,070	113,160	113,160	231,110	210,160	101,490	220,810	220,330	155,520
Maximum Capacity	242,902	242,902	242,902	234,122	234,122	234,122	225,342	225,342	225,342
Minimum Capacity	90,650	90,650	90,650	77,881	77,881	77,881	64,691	64,691	64,691

The maximum capacity values denote the slack capacity value that is computed when the demand is assigned for all partners with the minimum processing times. Since different partners have different processing times for different orders, two equal network configurations (in terms of partners) can have different total slack capacity values.

5.5.2. Analysis

The solutions to the scenarios are analyzed in Figure 36, Figure 37 and Figure 38. Figure 36 presents the total slack time and the total slack capacity values found for the low demand and low partner selection cost, medium demand and low partner selection cost and high demand low partner selection cost scenarios. In these scenarios, the cost of adding a new partner to the network is very cheap. It is observed that, in all of the three scenarios, the candidate DMNs include all SME Network partners. Since the maximum capacity value of low demand scenario is higher than the maximum capacity values of medium demand and high demand scenarios; the total slack capacity values are also higher. However, when the weight of slack time is equal to or higher than 0.8 (for low demand scenario) it becomes expensive for the DMN to keep all SME Network partners. After this weight, the total slack capacity decreases in the low demand scenarios.

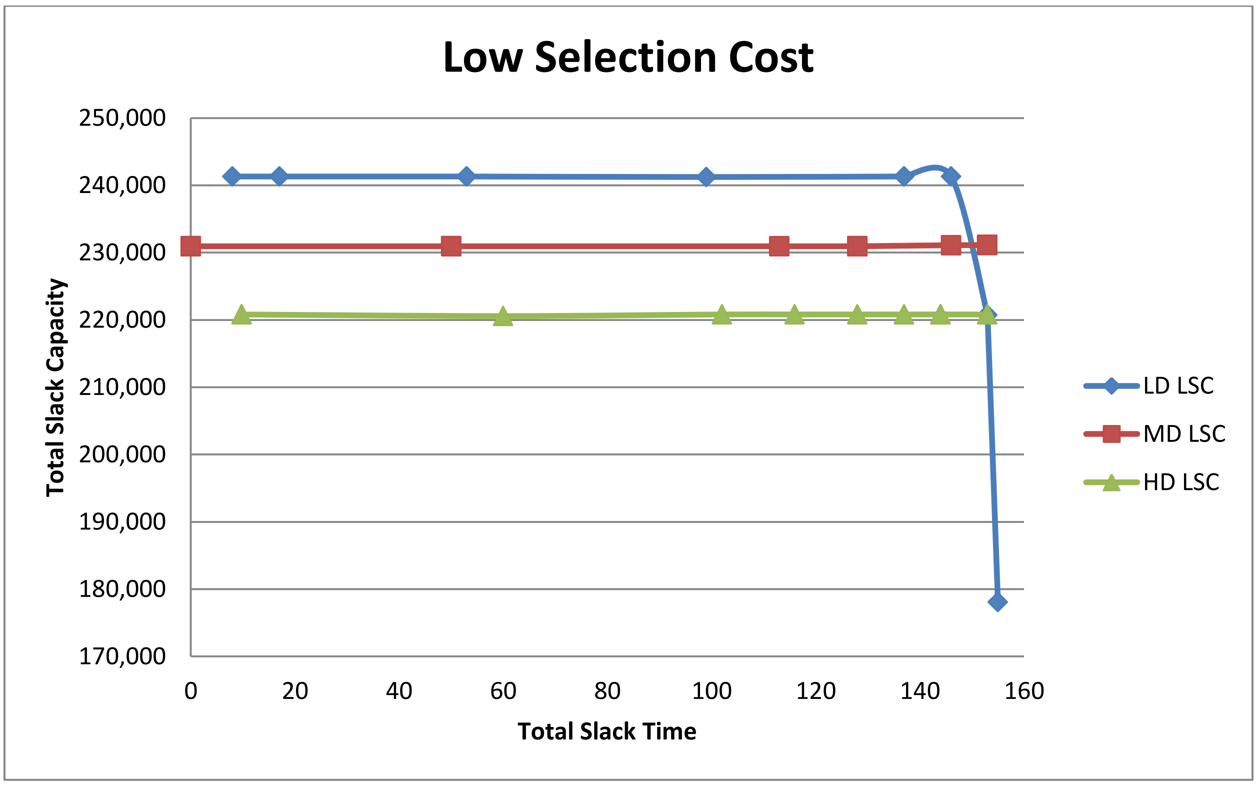

Figure 36 Total Slack Capacity and Total Slack Time Values for Low Selection Cost Scenarios

Figure 37 presents the total slack time and the total slack capacity values found in the low demand and medium partner selection cost, medium demand and medium partner selection cost and high demand and medium partner selection cost scenarios. For low demand values, it is observed that, that the optimal total slack capacity values are consistently lower than the optimal total slack capacity values of medium demand and high demand scenarios. Under medium partner selection cost setting, it will be expensive for the low demand scenario to include as many partners to the network as the medium demand and high demand scenarios. On the other hand, the medium demand scenario total capacity values are also higher than the high demand scenario values, except the solution where weight of slack capacity is equal to 0. This difference occurs, since the maximum total slack capacity available for high demand scenario is lower than medium demand scenario. On the other hand, it is important to note that the high demand scenario solutions includes all partners, for all solutions and has slightly higher capacity than the medium demand scenario solution when the weight of slack time is taken as 1.

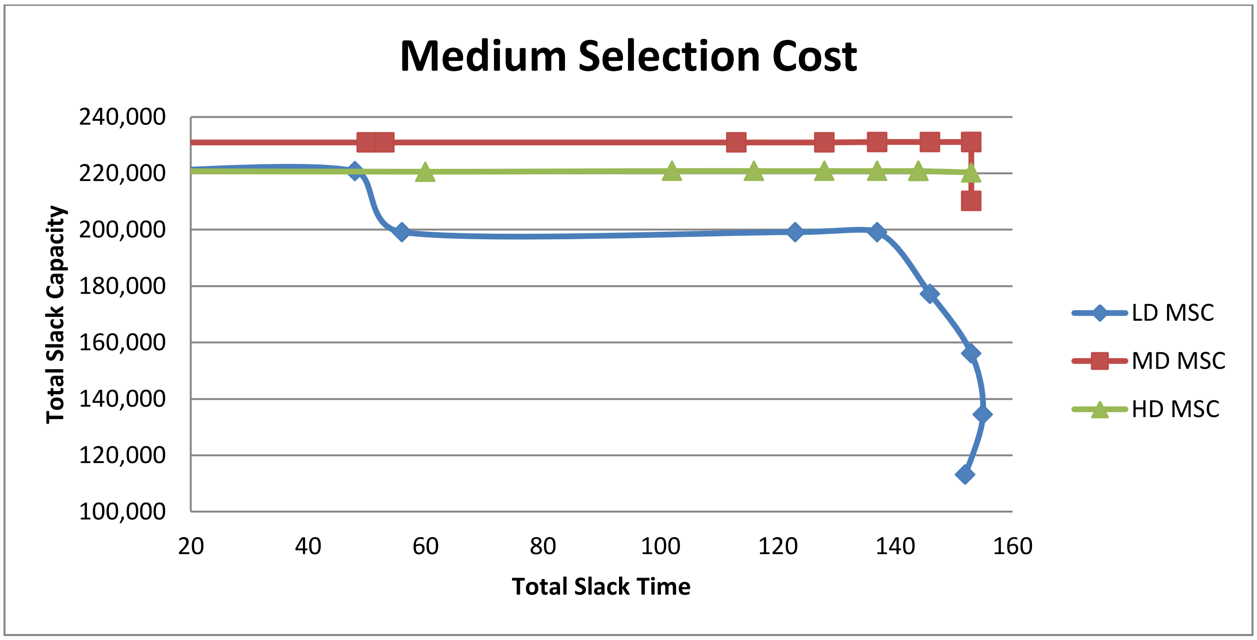

Figure 37 Total Slack Capacity and Total Slack Time Values for Medium Selection Cost Scenarios

Figure 38 presents the total slack time and the total slack capacity values found for the low demand and high partner selection cost, medium demand and high partner selection cost and high demand and high partner selection cost scenarios. The economies of scale effects become more visible in high partner selection cost scenarios. Therefore, scenarios with higher demand values tend to form DMNs with higher slack capacities. In this setting, the high demand scenario has the highest total slack capacity values even though it holds the lowest maximum capacity values. On the other hand, the medium demand scenario solutions vary in a wide range with different total slack capacity and total slack time values.

The total slack time value found in the medium demand scenario (for weight of total slack time is equal to 1) is lower than the total slack time values found by giving lower weights to slack time objective function. Finally, it is observed that, the low demand scenario have the lowest total slack capacity values. Since partner selection costs consists a higher percentage of their total cost values, the candidate solutions could not afford to increase as many partners as the other two scenarios.

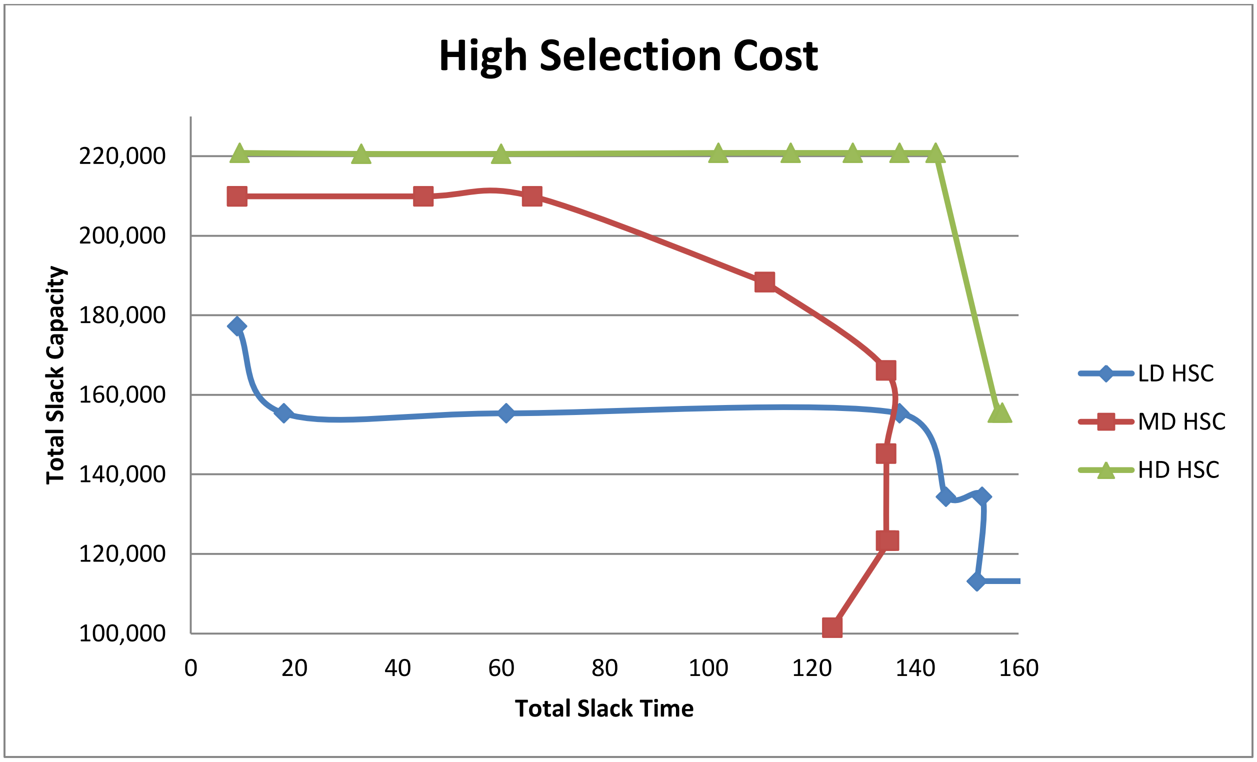

Figure 38 Total Slack Capacity and Total Slack Time Values for High Selection Cost Scenarios

Finally, we have compared the number of partners involved in each candidate DMN. Figure 39 presents the number of partners involved in each DMN for all of the 11 solutions found by giving different slack time and slack capacity weights. . The Scenario that brings the lowest number of partners is the low demand and high partner selection cost scenario. The number of partners involved in the DMNs created in low demand and high partner selection cost scenario varies between 6 and 8. It is important to remember that, for rescheduling lower lot sizes, lower slack capacity is required. So a DMN constituted by a small number of partners for a small order size can be as effective as a DMN constituted by high number of partners for a big order size in terms of rescheduling capability. On the other hand, another concern in these networks is about "process flexibility". Including more partners do not only increase the capability to reschedule disruptions, but also minimizes the risk of failure by distributing risk among many partners. In a DMN that is composed of few partners, if a partner fails to operate on time the harm is higher than the failure of a partner in a DMN that is composed of many partners. So even though small number of partners is enough for small order lot sizes, a DMN that is composed of higher number of partners is always more advantageous.

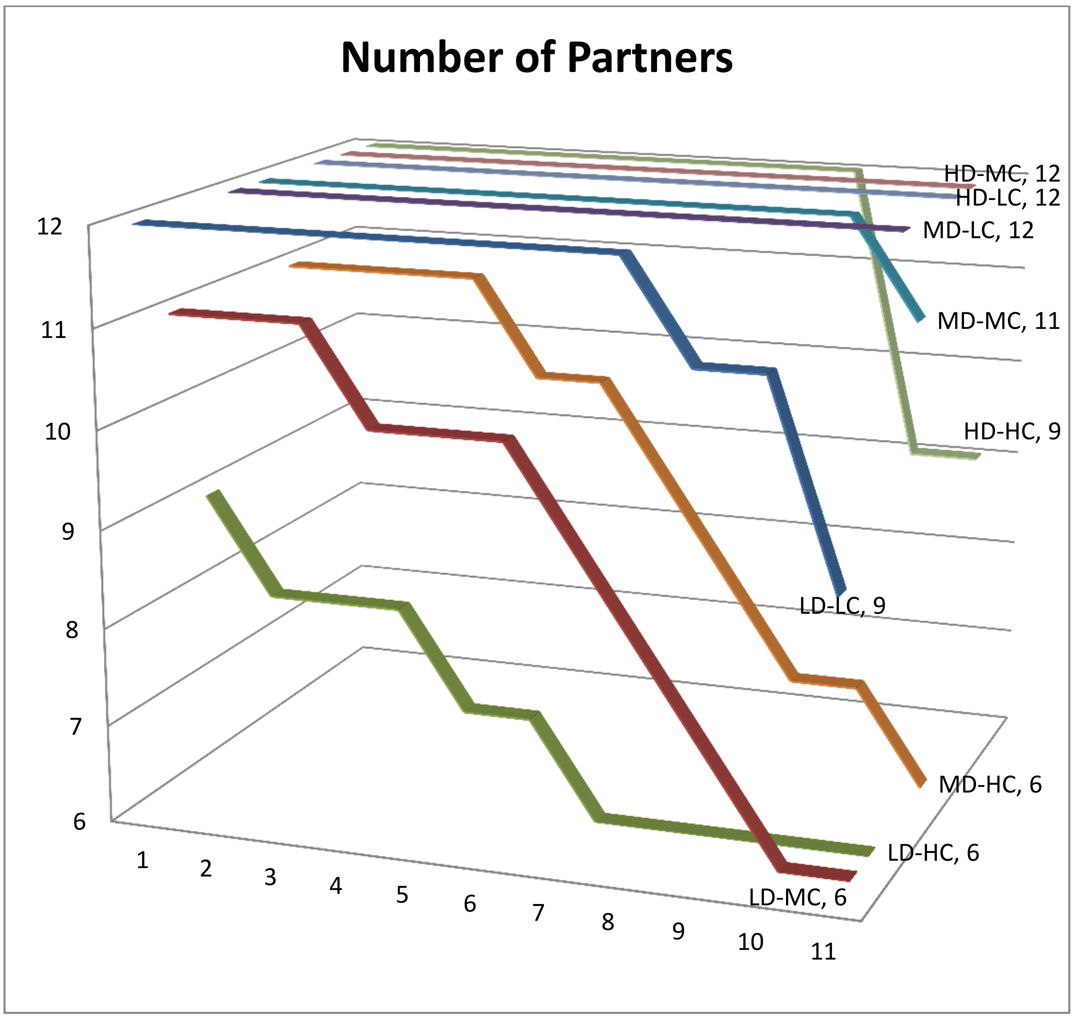

Figure 39 Number of Partners Included in the Created DMNs

The main observation obtained through the graph is the tendency of an increase in the number of partners as the demand values increase. Similarly as the partner selection cost values increase, the number of partners involved in the constituted DMNs tend to decrease.

5.6. CONCLUSIONS

In this chapter, we have proposed a multi objective MILP model for flexibility based DMN formation process and operational planning. Initially a framework on the loss prevention process is proposed for the stages of DMN risk management processes, from uncertainty to loss. The framework identifies reactive flexibility as the last means of prevention before order loss. Among several reactive flexibility measures, we have selected Slack Lead Time, and Slack Capacity as a way to integrate reactive flexibility strategies into planning. Later, mathematical programming formulations were developed for these two flexibility types, and these two measures were integrated as additional objectives to the cost minimization MILP model. An illustrative example was presented, in order to show the results with respect to different objective weights. Finally, we have created several scenarios with varying demand and partner selection cost values, aiming to understand tradeoffs of multiple objectives and to observe the model behavior.

Several observations can be extracted from this work. Through the application of the illustrative example, we have concluded that the decision makers will be more likely to select DMN configurations that are obtained through giving higher cost weights and lower flexibility weights. Even though high flexibility weights bring very flexible DMN configurations, the associated higher costs will make the solutions less favorable. It is also important to remind that, through integrating reactive flexibility measures; the DMN includes a capability to react future disruptions. Under these conditions creating a fully flexible network can be considered as less than ideal. The aim of the decision maker, while selecting the final DMN configuration should be choosing a DMN that has balanced slack time and slack capacity values that comes with a reasonable cost.

On the other hand, through the scenario analysis, we had the opportunity to observe how different demand values and partner selection costs affect the final DMN configuration and objective values. When partner selection cost is low, all demand scenarios can afford including as many partners to the constituted DMN and due to the lower utilization rate, lower demand scenarios bring higher slack capacity. On the other hand, it is observed that as the selection costs increase, only higher demand scenarios can afford including more partners to the network and end up with solutions that have higher total slack capacity and number of partners involved.

The scenario analysis also confirms the effectiveness of the DMN business model in terms of flexibility. Since the ICT system and SME Network provide a base for DMN constitution, it decreases the partner selection costs compared to less integrated collaborative business models. As a result of this advantage, the developed DMNs can afford more slack capacity flexibility than networks developed through less integrated business models.

Slack lead time and slack capacity are two important measures for operational flexibility. Both of the measures increase the capability of a DMN's to reschedule delayed orders. Balanced trade-off solutions (for slack time and slack capacity) are in general promising to increase reactive flexibility of the networks.

CHAPTER 6: RELIABILITY AND FLEXIBILITY IN DYNAMIC MANUFACTURING NETWORK PLANNING

This chapter aims to integrate both "order priority-driven reliability" and "reactive flexibility" measures into the formation process and operational planning of Dynamic Manufacturing Networks. By giving different weights to the different objective functions, we aim to better explore the various network structures and the space of trade-off solutions. Our final goal is to propose balanced solutions to the decision makers, with high reliability and flexibility values, along with fair costs.

6.1. INTRODUCTION

In this part of the work, we propose different configurations and plans of Dynamic Manufacturing Networks through a multi-objective model that is based on reliability, flexibility and cost objective functions. In order to come up with this MILP model, we have integrated two flexibility measures (slack capacity and slack time) presented in Chapter 5 (Section 3.2) with the mathematical formulation of Chapter 4 (Section 3.3).

By using the three objective functions (cost, reliability and flexibility) we will be able to create network structures that tackle different stages of the lost prevention process. While maximizing reliability of the network minimizes the risk of disruption occurring in the operational execution phase, maximizing reactive flexibility increases the chances of disruption mitigation. By changing the weights of the three objectives, we aim to explore the various network structures and the space of trade-off solutions. Through this exploration we intend to find both reliable and flexible DMN structures, with fair costs.

6.2. COMPUTATIONAL TESTS

In order to understand how the model responds to different objective weights, we have created three scenarios. Using the same data set that was used through the rest of the study, we have designed network configurations for "reliability maximization and cost minimization", "flexibility maximization and cost minimization" and "reliability maximization, flexibility maximization and cost minimization". The sections below present and interpret the results for the three different scenarios.

6.2.1. MAXIMUM RELIABILITY AND MINIMUM COST

Table 43 presents the total cost, total reliability, total slack capacity and total slack time, optimal values for different combinations of cost and reliability weights. In this example, we have explored DMN structures with reliability and cost concerns, and omit flexibility. However we have also calculated the flexibility values of the proposed network. As Table 43 suggests, the pure minimum cost solution has a cost of 140,970 and pure reliability solution has a reliability value of 1393.8. These values came out in accordance with the results of Chapter 4. When flexibility is ignored in the objective function, as seen from the results, total slack time and total slack values come out very low. This network structure minimizes the risk of disruption in the operational execution but still does not leave any slack for disruption mitigation.

Table 43 Maximum reliability, minimum cost solution (1/2)

Solution	W Cost	W Reliability	W Flexibility	Total Cost	Total Reliability	Total Slack Capacity	Total Slack Time
1	0.00	1.00	0.00	165,130	1393.80	93,581	156.00
2	0.10	0.90	0.00	157,630	1393.80	93,581	0.00
3	0.20	0.80	0.00	155,310	1384.70	115,460	0.00
4	0.30	0.70	0.00	155,310	1384.70	115,460	0.00
5	0.40	0.60	0.00	154,910	1381.70	115,360	0.00
6	0.50	0.50	0.00	154,910	1381.70	115,360	0.00
7	0.60	0.40	0.00	144,450	1189.80	156,960	3.00
8	0.70	0.30	0.00	141,820	1114.20	156,860	12.00
9	0.80	0.20	0.00	141,410	1090.10	135,720	9.00
10	0.90	0.10	0.00	140,970	1057.00	113,730	0.00
11	1.00	0.00	0.00	140,970	1057.00	113,730	0.00

Table 44 presents the unit costs of reliability, slack capacity and slack time, for the different scenarios. Cost of unit reliability is minimum at the solutions 5 and 6. Cost of unit slack capacity is minimum at the solution 8.

On the other hand, for solutions 2, 3, 4, 5, 6, 10, and 11 the total slack time is 0 therefore the unit cost is undefined. A balanced alternative with minimum unit reliability cost, is found in solutions 5 and 6. This solution has a cost of 154,910 and reliability of 1381.7. The network configuration for the balanced solution is found as N1, N6, N7, N9, N11 and N12. The slack capacity associated with this solution is found as 115360 and slack time is found as 0. When only reliability and cost is taken into account in the objective function the flexibility values come out very low.

Table 44 Maximum reliability, minimum cost solution (2/2)

Solution	Cost of Unit Reliability	Cost of Unit Slack Cap	Cost of Unit Slack Time	Network Configuration
1	118.47	1.76	1058.53	N1,N6,N7,N9,N12
2	113.09	1.68	#DIV/0!	N1,N6,N7,N9,N12
3	112.16	1.35	#DIV/0!	N1,N6,N7,N9,N11,N12
4	112.16	1.35	#DIV/0!	N1,N6,N7,N9,N11,N12
5	112.12	1.34	#DIV/0!	N1,N6,N7,N9,N11,N12
6	112.12	1.34	#DIV/0!	N1,N6,N7,N9,N11,N12
7	121.41	0.92	48150.00	N1,N3,N6,N7,N8,N9,N10,N12
8	127.28	0.90	11818.33	N1,N3,N6,N7,N8,N9,N10,N12
9	129.72	1.04	15712.22	N3,N6,N7,N8,N9,N10,N12
10	133.37	1.24	#DIV/0!	N3,N6,N8,N9,N10,N12
11	133.37	1.24	#DIV/0!	N3,N6,N8,N9,N10,N12

6.2.2. Maximum Flexibility And Minimum cost

Table 45 presents the total cost, total reliability, total slack capacity and total slack time, optimal values for different combinations of cost and flexibility weights. The weight of reliability in the objective function in this scenario is taken as 0. In other words, we have created the network with flexibility and cost concerns, and omit reliability.

In this example, weights of the two flexibility components are equal. For instance, while in solution 1, both slack time and slack capacity weights were taken as 0.5, in solution 2 they were both taken as 0.45. We have also calculated the reliability values of the proposed network. As Table 45 suggests, the cost value of the pure minimum cost solution is also found as 140,970. On the other hand, in the pure flexibility solution, the slack capacity is 243,380 and the slack time is 189. When reliability is ignored in the objective function, reliability values come out very low. This network structure maximizes the capability to mitigate disruptions, while not increasing reliability of the network. In a reliable network, disruptions are less likely to occur. Table 46 presents unit costs for reliability, slack capacity and slack time. The cost of unit slack time is minimum at solutions 2 and 3. The cost of unit slack capacity is at its minimum, in solutions 5 and 6. Since the total reliability solution does not vary much within the solution pool, the cost of unit reliability continuously decreases as the total weight decreases.

Table 45 Maximum flexibility, minimum cost solution (1/2)

Solution	Wcost	W Flex	W Reliability	Total Cost	Total Sl Cap	Total Sl Time	Total Reliability
1	0	1	0	180,070	243,380	189.0	1,076.1
2	0.1	0.9	0	156,960	241,980	189.0	1,076.6
3	0.2	0.8	0	156,960	241,980	189.0	1,076.6
4	0.3	0.7	0	153,660	241,980	180.0	1,076.6
5	0.4	0.6	0	152,460	241,980	174.0	1,076.6
6	0.5	0.5	0	152,180	241,780	172.0	1,091.0
7	0.6	0.4	0	148,710	221,240	162.0	1,096.5
8	0.7	0.3	0	146,450	199,670	153.0	1,090.0
9	0.8	0.2	0	144,260	156,860	132.0	1,114.2
10	0.9	0.1	0	141,310	113,730	45.0	1,057.0
11	1	0	0	140,970	113,730	0.0	1,057.0

The solutions with minimum unit slack time cost and low unit slack capacity cost, are solutions 2 and 3. These solutions have a cost of 156,960, slack capacity of 241,980 and slack time of 189. Even though unit costs are high in these solutions, one can see that flexibility levels are very high. It is not efficient to pay a lot for high flexibility in order to provide a sufficient level of flexibility. We can rather choose solution 7 that has high flexibility values, along with the highest reliability value.

Table 46 Maximum flexibility, minimum cost solution (2/2)

Solution	Cost of Unit Sl Time	Cost of Unit Capacity	Cost of Unit Reliability	Network Configuration
1	952.75	0.74	167.34	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
2	830.48	0.65	145.79	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
3	830.48	0.65	145.79	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
4	853.67	0.64	142.73	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
5	876.21	0.63	141.61	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
6	884.77	0.63	139.49	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
7	917.96	0.67	135.62	N1,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
8	957.19	0.73	134.36	N1,N3,N4,N5,N6,N7,N8,N9,N10,N12
9	1,092.88	0.92	129.47	N1,N3,N6,N7,N8,N9,N10,N12
10	3,140.22	1.24	133.69	N3,N6,N8,N9,N10,N12
11	#DIV/0!	1.24	133.37	N3,N6,N8,N9,N10,N12

6.2.3. *MAXIMUM FLEXIBILITY, MAXIMUM RELIABILITY AND MINIMUM COST*

Table 47 presents the total cost, total reliability, total slack capacity and total slack time, optimal values found for different combinations of cost, reliability and flexibility weights. In this experimental setting, all the three objective functions are taken into account. Within the three objective functions we have changed the cost weight, while taking reliability and flexibility values equal. In this example, within the flexibility objective, the weights of slack time and slack capacity are also taken equal.

As Table 47 suggests, the pure minimum cost solution has a value of 140,970. On the other hand, in solution 1, where reliability and flexibility objectives were equally maximized, the total cost has a value of 195,840 with 1362.8 total reliability, 189 total slack time and 239,630 total slack capacity.

Table 47 Maximum flexibility, maximum reliability, minimum cost solution (1/2)

Solution	W cost	W reliability	W Flexibility	Total Cost	Total Slack Time	Total Slack Capacity	Total Reliability
1	0.00	0.50	0.50	195,840	189.00	239,630	1362.80
2	0.10	0.45	0.45	175,380	189.00	240,080	1334.30
3	0.20	0.40	0.40	166,750	182.00	240,880	1301.70
4	0.30	0.35	0.35	154,660	172.00	241,980	1182.50
5	0.40	0.30	0.30	152,960	162.00	242,080	1167.50
6	0.50	0.25	0.25	146,550	155.00	199,670	1090.00
7	0.60	0.20	0.20	144,650	146.00	156,860	1114.20
8	0.70	0.15	0.15	142,220	48.00	156,860	1114.20
9	0.80	0.10	0.10	142,220	48.00	156,860	1114.20
10	0.90	0.05	0.05	141,010	18.00	113,730	1057.00
11	1.00	0.00	0.00	140,970	0.00	113,730	1057.00

Table 48 presents unit costs for reliability, slack capacity and slack time. The cost of unit slack time is minimum at solution 4. The unit reliability cost fluctuates through the solutions and is at its minimum at solution 8. Solutions 4 and 5, on the other hand, have the lowest unit slack capacity and slack time values.

Depending on how much the decision makers are willing to pay for risk minimization and disruption mitigation, one of the solutions will be selected. For example, solution 4 provides a good balance between total slack time, slack capacity and reliability values and has a cost of 154,660.

Table 48 Maximum flexibility, maximum reliability, minimum cost solution (2/2)

Solution	Cost of Unit Slack Time	Cost of Unit Slack Cap	Cost of Unit Reliability	Network Configuration
1	1036.19	0.82	143.70	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
2	927.94	0.73	131.44	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
3	916.21	0.69	128.10	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
4	899.19	0.64	130.79	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
5	944.20	0.63	131.01	N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11,N12
6	945.48	0.73	134.45	N1,N3,N4,N5,N6,N7,N8,N9,N10,N12
7	990.75	0.92	129.82	N1,N3,N6,N7,N8,N9,N10,N12
8	2962.92	0.91	127.64	N1,N3,N6,N7,N8,N9,N10,N12
9	2962.92	0.91	127.64	N1,N3,N6,N7,N8,N9,N10,N12
10	7833.89	1.24	133.41	N3,N6,N8,N9,N10,N12
11	#DIV/0!	1.24	133.37	N3,N6,N8,N9,N10,N12

By paying 10% more than the minimum cost, a solution with high reliability and flexibility values can be attained. However, if this level of risk mitigation is not required and is considered as unnecessary, solution 7 might also be a good choice with a cost of only 144,650. This solution has values of 1114.2 for reliability, 156,860 for total slack capacity and 146 for total slack time.

6.3. COMPARISONS

We now compare the optimal values of the objective functions found in three scenarios: maximum reliability; maximum flexibility; and maximum flexibility and reliability.

6.3.1. TOTAL COST

Initially, we have analyzed the total cost values of the three scenarios. As Table 49 presents, 11 solutions to maximum reliability, maximum flexibility and maximum flexibility and reliability scenarios were calculated. This was done by changing the weight of the cost and the objective under analysis in the multi objective model. For example, in the maximum reliability scenario, the weights of cost and reliability sum to 1, while the flexibility weight is 0. On the other hand, in the maximum flexibility scenario, the reliability objective weight is considered as 0.

Table 49 Total cost values of models

Solution	W cost	Max Reliability	Max Flexibility	Flexibility Reliability
1	0.00	165,130	180,070	195,840
2	0.10	157,630	156,960	175,380
3	0.20	155,310	156,960	166,750
4	0.30	155,310	153,660	154,660
5	0.40	154,910	152,460	152,960
6	0.50	154,910	152,180	146,550
7	0.60	144,450	148,710	144,650
8	0.70	141,820	146,450	142,220
9	0.80	141,410	144,260	142,220
10	0.90	140,970	141,310	141,010
11	1.00	140,970	140,970	140,970

In the maximum flexibility and reliability scenario, the weights of flexibility and reliability are taken equal. For example, in solution 1, the weight of cost is taken as 0. In this solution, both weights for flexibility and reliability are taken as 0.5.

As seen from Figure 40, increasing the weight of flexibility or the weight of reliability or both increase the total cost of the operational model. Thus both flexibility and reliability comes with a cost. We can also observe that targeting a both fully reliable and flexible solution comes with a higher cost than focusing on only reliability or on flexibility alone. The costs of the maximum reliability and the maximum flexibility scenarios come out very close to each other, and follow a similar trend. For weights of cost higher than 0.3, we can see that the cost values of all three scenarios come out with similar results. Thus the decision makers can select a solution depending on the reliability and flexibility values of the solutions, and taking into account how much they are willing to pay for extra flexibility and reliability.

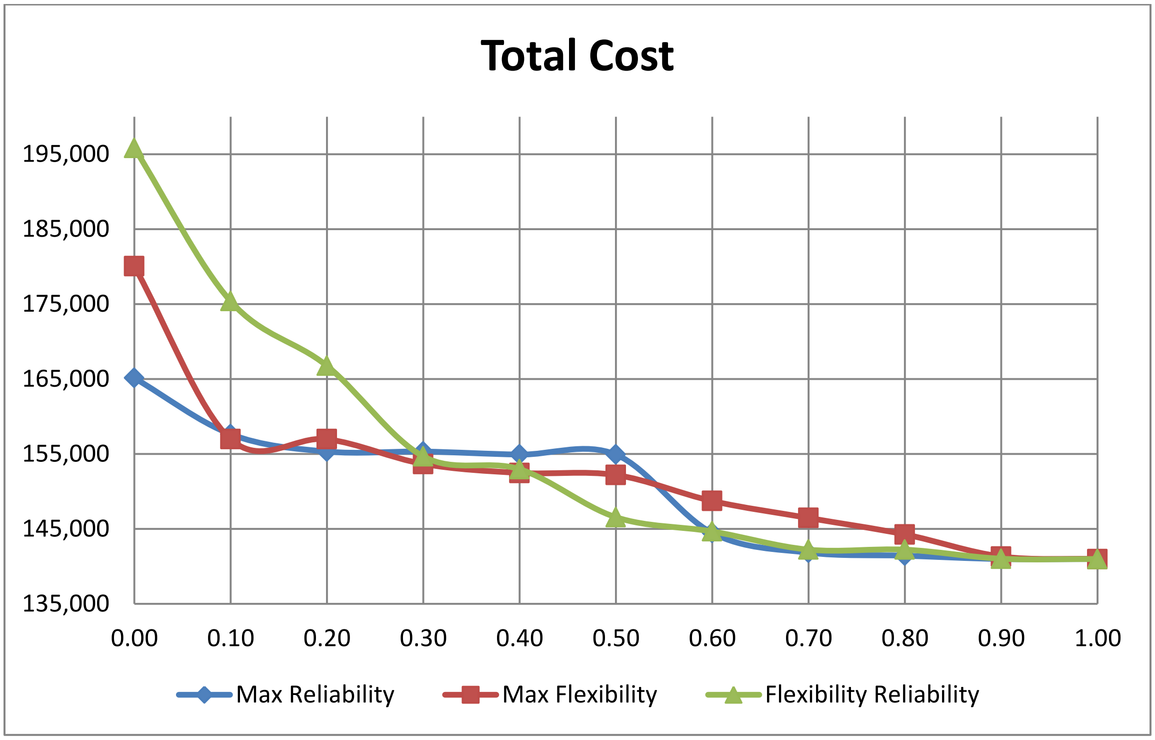

Figure 40 Total cost function of models

6.3.2. Total Reliability

Table 50 presents the total reliability values computed for the three scenarios. Figure 41, on the other hand presents the graph of the total reliability values for the three scenarios (with respect to different cost weights). When we compare reliability values of the three solutions, we can see that maximum reliability values come with the maximum reliability scenario. The second highest values are obtained by the flexibility and the reliability scenarios. And the lowest reliability values come out with the maximum flexibility scenario.

However, when the weight of cost is equal or larger than 0.7 in the objective function, all of the three scenarios lead to similar reliability values. Even though the total costs of the three scenarios are very close and the total reliability scenario has reasonably higher reliability values, flexibility values should also be checked before selecting a network structure and an operational plan.

Table 50 Total reliability values of the models

Cost Weight	Max Reliability	Max Flexibility	Flexibility Reliability
0	1393.80	1,076.1	1362.80
0.1	1393.80	1,076.6	1334.30
0.2	1384.70	1,076.6	1301.70
0.3	1384.70	1,076.6	1182.50
0.4	1381.70	1,076.6	1167.50
0.5	1381.70	1,091.0	1090.00
0.6	1189.80	1,096.5	1114.20
0.7	1114.20	1,090.0	1114.20
0.8	1090.10	1,114.2	1114.20
0.9	1057.00	1,057.0	1057.00
1	1057.00	1,057.0	1057.00

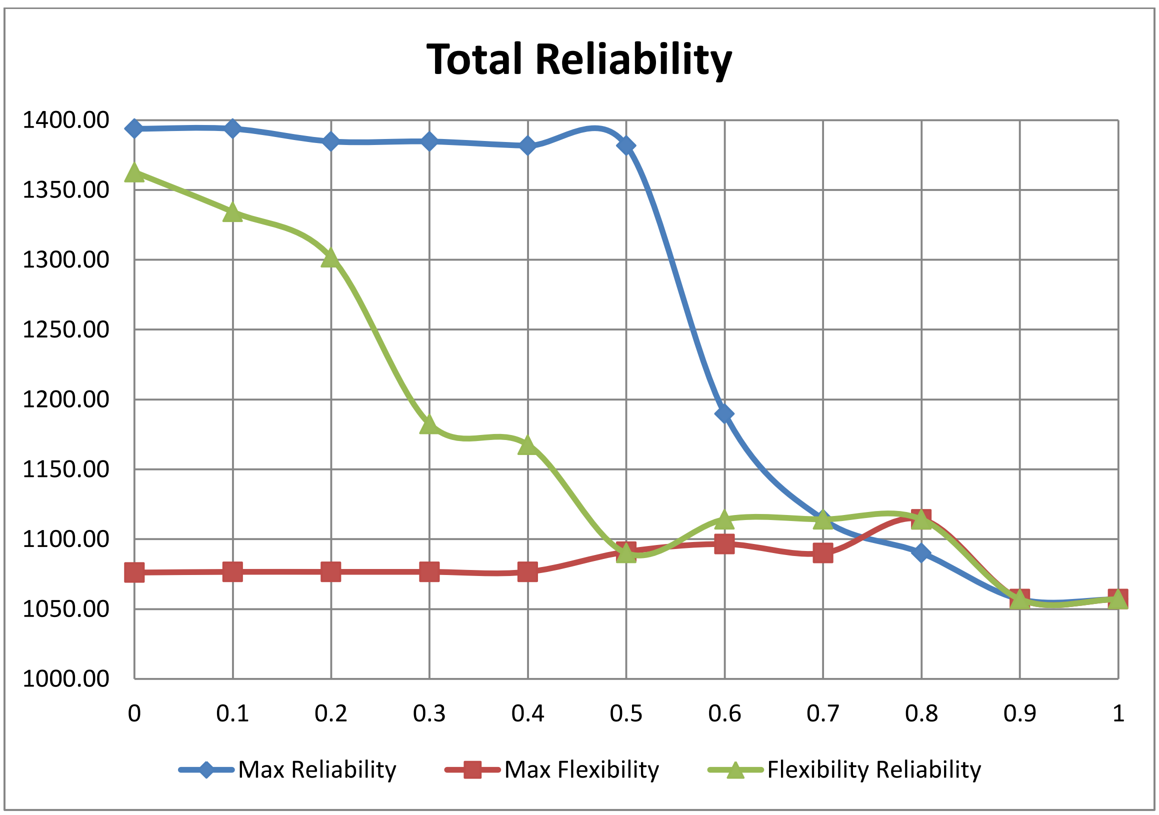

Figure 41 Total reliability function of the models

6.3.3. *Total Slack Time*

Table 51 presents the total slack time values found for the three scenarios. Figure 42 shows how total slack time values change with respect to different cost weights. The slack time values of the maximum flexibility and maximum reliability and flexibility scenarios, for cost weights smaller and equal to 0.3, are very close to each other. On the other hand, the slack time values found for the maximum reliability scenario tend to be very low. Maximizing reliability and minimizing cost will lead to an operational plan where lots are scheduled as late as possible among the most reliable partners. Due to this tendency, the total slack time values of the maximum reliability scenario come out very small.

Table 51 Total slack time values of the models

Cost Weight	Max Reliability	Max Flexibility	Flexibility Reliability
0	156.00	189.0	189.00
0.1	0.00	189.0	189.00
0.2	0.00	189.0	182.00
0.3	0.00	180.0	172.00
0.4	0.00	174.0	162.00
0.5	0.00	172.0	155.00
0.6	3.00	162.0	146.00
0.7	12.00	153.0	48.00
0.8	9.00	132.0	48.00
0.9	0.00	45.0	18.00
1	0.00	0.0	0.00

6.3.4. Total Slack Capacity

Finally we have compared the total slack capacity values for the three scenarios, with different weights (see Table 52). As shown in Figure 43, the highest total slack capacity values are found in the maximum flexibility scenario. The second highest values are obtained by maximizing both reliability and flexibility. The maximum reliability scenario leads to the lowest total slack capacity values. Note that maximizing reliability requires assigning all production to the most reliable partners, and this may result in including very few partners into the network configuration.

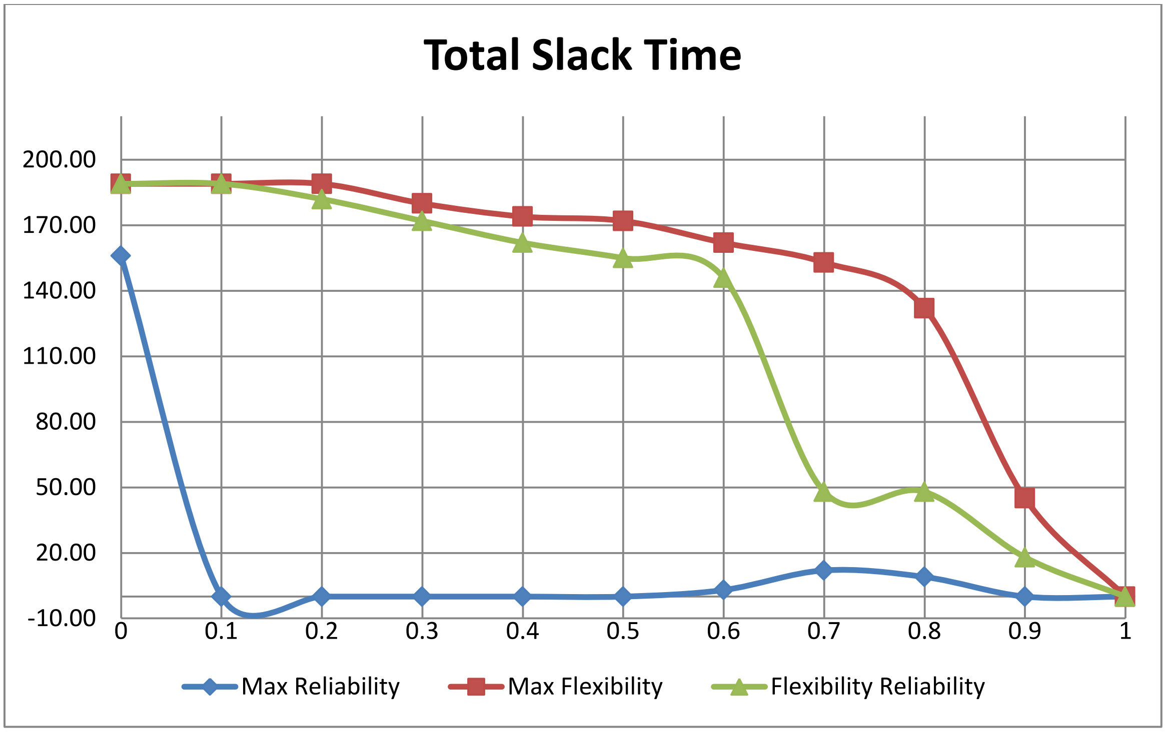

Figure 42 Total slack time function of the models

Table 52 Total slack capacity values of the models

Cost Weight	Max Reliability	Max Flexibility	Flexibility Reliability
0	93,581	243,380	239,630
0.1	93,581	241,980	240,080
0.2	115,460	241,980	240,880
0.3	115,460	241,980	241,980
0.4	115,360	241,980	242,080
0.5	115,360	241,780	199,670
0.6	156,960	221,240	156,860
0.7	156,860	199,670	156,860
0.8	135,720	156,860	156,860
0.9	113,730	113,730	113,730
1	113,730	113,730	113,730

It should be noted that, in order to increase reactive flexibility of a network, it is not only necessary to cut slack capacity but also slack time. In order to provide better suggestions for the network selection, all of the objective function values should be taken into account.

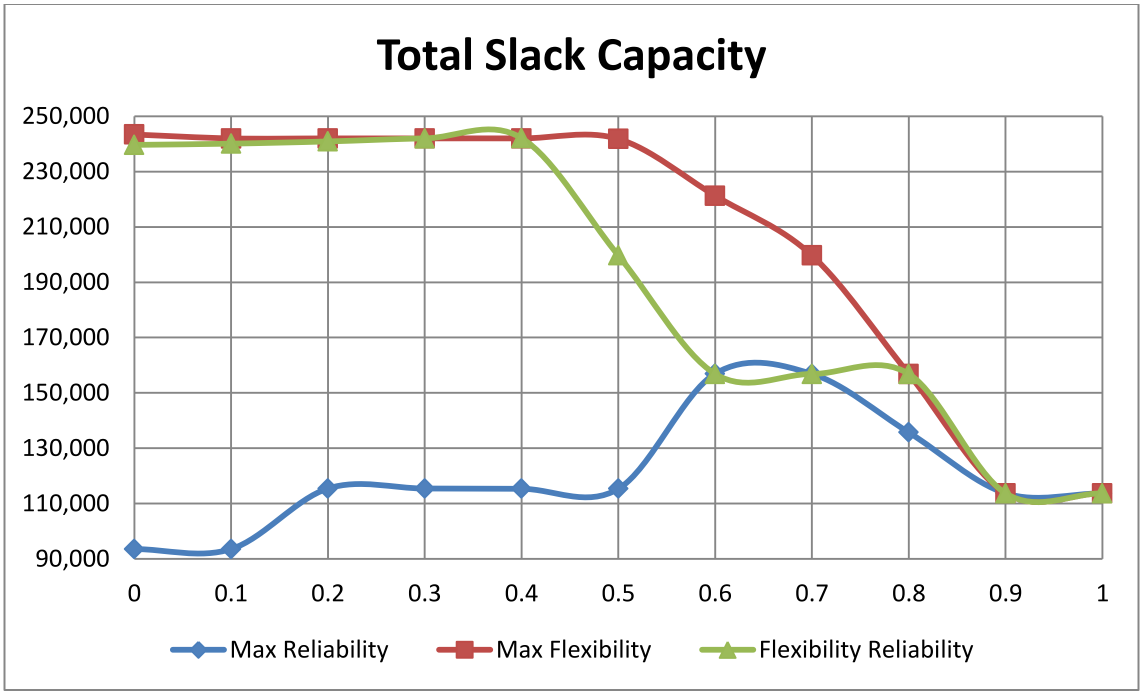

Figure 43 Total slack capacity functions of the models

6.4. Network Structure

Here we will present three alternative network configurations, with different values for total flexibility, total reliability and total cost. Table 53 shows the maximum and the minimum values each objective function can take. These values may give the decision makers an understanding of how close the solutions are when compared to the optimal values. The total cost values vary between 140,972 to 180,000, the total reliability values vary between 752.44 to 1393.8, the total slack time values vary between 0 to 189 and total the slack capacity values vary between 91,317 to 243,382.

Table 53 Maximum and minimum values of the objective functions

Column1	Cost	Reliability	Slack Time	Slack Capacity
Minimum	140972	752.44	0	91317
Maximum	180000	1393.8	189	243382

Below, we present the optimal solutions found for three different weight configurations. These network configurations are intended to represent different trade-off solutions for cost, reliability and flexibility.

6.4.1. NETWORK 1

First, Figure 44 shows the configuration of network 1. This network was created with the following weights: 0 for cost, 0.5 for flexibility and 0.5 for reliability.

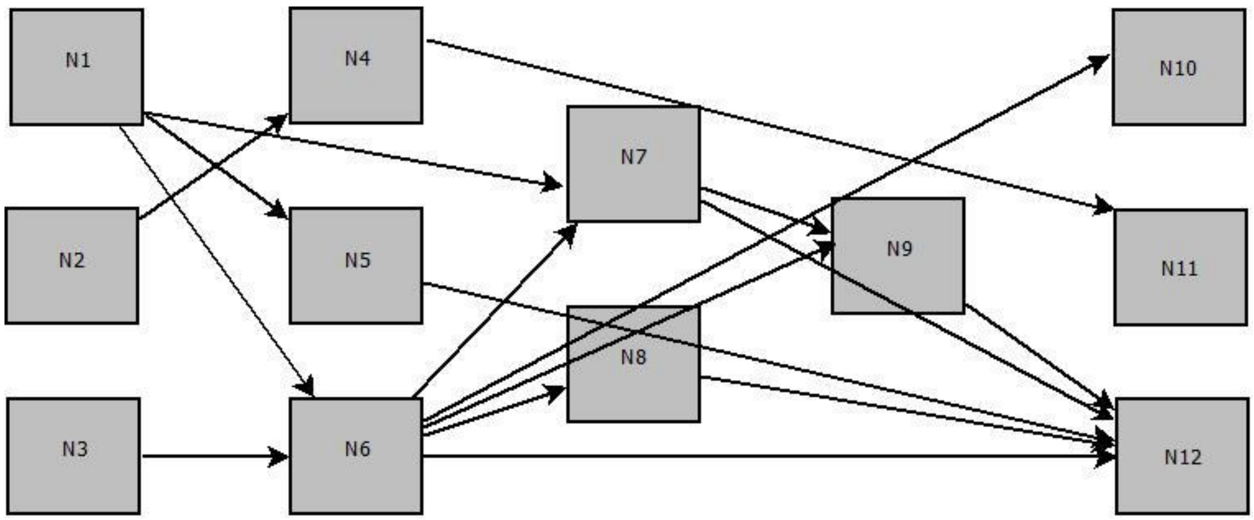

Figure 44 Representation of network 1

Network 1 can be viewed as the DMN that leads to the better trade-off between reliability and flexibility. Cost has been ignored in creating Network 1. The total cost of the network comes out as 195,840 which is 39 % higher than the minimum cost to form a DMN. The total Slack time value is at its maximum as 189, total slack capacity is only 2% below its maximum and total reliability is only 5% below its maximum.

As seen from Figure 44, this network includes all 12 potential partners. Even though including a new partner to the network adds a selection cost to the plan, in order to maximize the total slack capacity, the maximum number of partners has been involved. The arrows in the network representation stand for the transportation links between different manufacturing partners.

6.4.2. NETWORK 2

Figure 45 shows the DMN that was created with the following weights: 0.3 for cost, 0.35 for reliability, and 0.35 for flexibility. This network consists of all the 12 network members:

N1, N2, N3 for operation 1; N4, N5, N6 for operation 2; N7, N8 for operation 3; N9 for operation 4; and N10, N11 and N12 for operation 5.

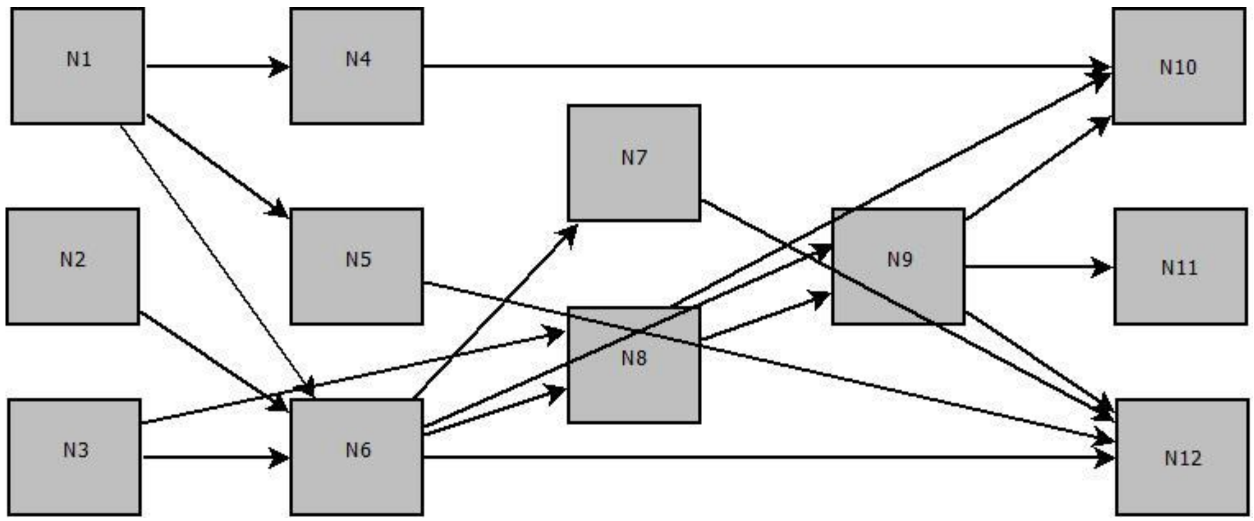

Figure 45 Representation of network 2

The total cost of forming network 2 is 154,660 which is 10 % higher than the minimum cost (140,972). The total slack time of this solution is 172 which is 91% of the maximum slack time (189). Total slack capacity is 241,980 which is 99% of the maximum slack capacity (243,382). The total reliability of this network configuration is 1182.5 which is 67 % of the total reliability value. Even though the partners involved in networks 1 and 2 are the same, the production and the transportation plans of the two network structures are very different.

This solution can be summarized to the decision makers as follows: if network configuration 2 is chosen, by paying 10% more than the minimum cost, it is possible to allow total slack capacity up to 99% of its maximum, the total slack time 91 % of its maximum and the total reliability to 67% of its maximum.

6.4.3. NETWORK 3

Finally the Network Configuration 3 is shown in Figure 46. It was created with the following weights: 0.6 for cost, 0.2 for reliability, and 0.2 for flexibility. The result is a DMN that is composed of: N1 and N3, for operation 1; N6, for operation 2; N7 and N8 for operation 3; N9 for operation 4; and N10 and N12 for operation 5.

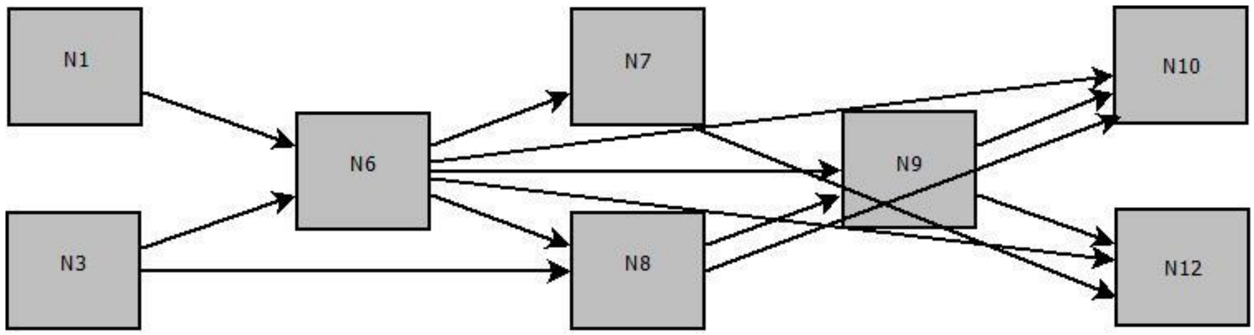

Figure 46 Representation of network 3

The total cost required to form this network is 144,650 which is only 3% higher than the minimum cost 140,972. As a result of paying this extra cost, it is possible to increase the total slack time to 146 (77 % of its maximum value 189), the total slack capacity to 156,860 (64% of its maximum value 243,382) and the total reliability to 1114.2 (56% of its maximum value 1393.8).

6.5. CONCLUSION

In this chapter of the dissertation, we have integrated the two perspectives presented in Chapters 4 and 5. While chapter 4 aimed at creating reliable DMNs in order to minimize the risk of disruption occurrence, chapter 5 was rather concerned with increasing the likelihood of mitigating disruptions.

In order to explore how the network structure and the values of objectives change with the weights, we have created three different test settings. In the first setting, we have just considered changes in the weights for reliability and cost, and have omitted flexibility. Then we have studied a scenario where maximum flexibility and minimum cost solutions were explored, while reliability was ignored. Finally, we have created different DMN configurations that consider all three objective functions, (cost, reliability and flexibility). Later, we have compared the optimal objective function values computed in the three different scenarios.

To illustrate our approach, we concluded this chapter, proposing three alternative network configurations to the decision makers with the associated values for total cost, total reliability, total slack time and total slack capacity. In this way, it is possible to support more educated decisions, in network formation and operational planning of DMNs, even if the result of the decision making process can differ from DMN to DMN depending on the importance of the end customer, or the perception of environmental risks, etc.

CHAPTER 7: CONCLUSIONS AND FURTHER DEVELOPMENTS

This chapter concludes the work performed in our doctoral research, listing its main contributions. The limitations of the work are also presented as well as several suggestions for future research.

7.1. CONTRIBUTIONS

In this thesis, we have proposed a set of methodologies and tools to support strategic, tactical and operational decisions in Dynamic Manufacturing Networks (DMN) of SMEs. In particular we have considered the application of our business model to the case of discrete complex manufacturing industries. The main objectives proposed in the beginning of the dissertation are successfully achieved as namely:

- Customizing the DMN business model for the context (Chapter 2)
- Developing frameworks and business processes that support the network vision (Chapter 3)
- Developing models to assist the DMN in formation and planning (Chapter 4, 5, and 6)

It is believed that, the most impactful contribution of this research is providing a top down, methodological and integrated approach to support SME collaboration in strategic, tactical and operational levels. The proposed work does not only plan and synchronize the daily interactions of SMEs in the operational base, but also connects them in the strategic level by setting a common vision that benefits all parties, and provides tactical level ICT tools by connecting them through an automated integrated platform. Moreover, these ICT tools support the SME network vision and link strategy with operation which makes the thesis unique. Collaborative Network formation and planning models are mostly developed to fulfill the instant needs of industry and therefore holistic and strategic perspectives are frequently neglected.

The applicability of such integrated business models is debatable due to their high level of dependency on trust and information sharing. However, given the turbulent nature of international markets and increasing connectedness in global economy, it is the time for SMEs to consider being a part of these business models. In order to join a collaborative network, a potential partner needs to be convinced that the overall (short term and long term) benefits of collaboration will be more than the overall benefits of competition. By explaining and highlighting the increased survival rate of potential partners within the business model and the global long term expansion of the SME network, the SMEs will be more willing for partnership and information sharing. Therefore, the SME network vision is an important contribution that needs to be highlighted and promoted.

The main contributions created in each chapter of the thesis are summarized as follows:

Chapter 2 proposed a new business model for SME collaboration in discrete complex manufacturing industries and identified a list of research opportunities. Moreover, a DMN taxonomy was also created by taking the Collaborative network taxonomy and DMN characteristics into account.

Chapter 3 created a common vision for the SME network with three dimensions: sustainability, growth and survival. Further on, the study translated the vision into operational level IT initiatives and functional, process and informational flows between modules are designed accordingly.

Chapter 4 proposed a new methodology that integrates customer, manufacturer and order characteristics into DMN formation and operational planning. The methodology encompasses TOPSIS, Fuzzy inference system and multi objective MILP approaches. Moreover, this chapter also demonstrated the application of a designed Decision Support System (DSS) for analyzing alternative network configurations, for varying alternative weights.

Chapter 5 presented a new methodology to support DMN formation and operational planning with reactive flexibility and cost concerns. Slack capacity and slack time are chosen as operational flexibility types and measures are formulated to compute their values. Later on, these formulations are embedded in a MILP model along with total cost. The methodology is able to create balanced solutions between total cost and total operational flexibility.

Chapter 6 also contributes to operational planning of DMNs by combining the perspectives developed in Chapter 4 and Chapter 5. The model allows creation of balanced candidate solutions that represent good trade-offs between cost, flexibility and reliability.

7.2. Limitations and Future Work

The most important limitation of this work is possibly the lack of real life examples and case studies. DMN applications require a holistic integration of supply chains and DMN members need to share private real time data on their capabilities, costs and capacities. It is important to mention that some DMN partners may have capabilities in similar or exactly the same areas and operations. DMN partners may be competitors in other supply chains, or they may target the same customers outside of DMNs. Because of these barriers between partners, a base level of trust has to be settled prior to DMN formation. In this dissertation, we have assumed the formation of a strategic partnership (the SME network) prior to the DMN formation. An SME network aims to create the necessary conditions and agreements for collaboration. During the development of the thesis, we could not find a real life application of an industrial strategic partnership willing to share the private data of its partners.

Another important limitation of this work was the lack of solution methodologies for large instances of the MILP models. We have developed MILP models (see Chapter 4 and 5) to create operational plans with different objective functions. These models are solved to optimality by using the IBM Ilog CPLEX software. Even though it is possible to solve small instances in short time (2 or 3 minutes) and medium instances in reasonable time, for large instances the software gave an "out of memory" alert and could not solve the models because of their complexity and size. It is clear that we need to develop heuristics for large instances since the DMN business model is specifically designed for industries that are characterized by complex manufacturing processes and with multiple manufacturing echelons. This limitation is a possible future direction for research.

Through the thesis we have developed approaches to support decision-making concerning different levels of the business model (SME Network and DMN). We have then developed a Conceptual Framework, and designed a set of ICT supported business functions and processes to operationalize the model (such as Group Cohesion Management, Membership Management, Customer Relations, DMN Life Cycle Management and Order Promising).We have also developed methodologies to support DMN creation(see Chapter 4 and 5).

However there are still other functions requiring ICT support. These modules need to work synchronously with the SME network database and with the Collaborative Platform, and exchange data internally. Future extensions of the study should cover detailed research on other modules of the business model. The end result is possibly a complete ICT system that supports an integrated and comprehensive set of automated decisions

Group cohesion management and Membership management decision support tools need to be created. Trust, reliability and fairness measures need to be developed and managed. Membership Management is another SME network function that was identified with the association, dissociation and profiling of SME network members. Decision support tools are also required to support this function according to the profiles and performances of the members.

For the e-commerce decision support tools based on mathematical models and algorithms need to be created particularly for customer prioritization and customer segmentation decisions. On the other hand, order promising function being responsible for the acceptance, prioritization and classification of orders, also requires the development of integrated or separate decision support tools.

This need for additional tools also exists for the other DMN functions (complementing the proposals presented in Chapters 4, 5 and 6.).

In Chapter 5 we have added two reactive flexibility measures into the MILP model. As a possible extension of this model, we might have more proactive and reactive flexibility measures. Integrating both types of flexibilities will lead to less process disruptions and more effective disruption mitigation. It would also be interesting to include other soft factors into the DMN creation process. Because of the collaborative structure of DMNs, social factors such as collaboration history, trust, cultural and human barriers can, in fact, play an important role(Camarinha-Matos and Afsarmanesh, 2007). A pure optimization model fails to address these soft concerns and needs therefore to be complemented by procedures of a different nature. This is surely an interesting topic for future research. Apart from these extensions, it is important and necessary to apply the developed methodology into case studies and contact with related audience to learn more about practical concerns. When all practical and theoretical study is finalized, it will be possible to create a real life application of the business model.

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APPENDIX

```
 C= {C1,C2, C3, C4, C5, C6, C7, C8};
 //Set of Customers

 O = {O1, O2, O3,O4,O5};
 //Set of operations

 K = {K1,K2,K3,K4,K5,K6,K7,K8,K9,K10};
 //Set of products

  T=6;
 //Planning horizon

 N = {N1, N2, N3, N4, N5, N6, N7, N8, N9, N10, N11, N12};

 WR=1;
 WC=0;
 Zmin=40;

P = [[      1      1      1      1      1      ]
[      1      0      1      1      1      ]
[      1      1      0      1      1      ]
[      1      1      0      0      1      ]
[      1      1      1      0      1      ]
[      1      1      0      1      1      ]
[      1      1      0      0      1      ]
[      1      1      0      0      1      ]
[      1      1      0      1      1      ]
[      1      1      1      0      1      ]]
;

 NO = [[     1 1   1   0   0   0   0   0   0   0   0   0   ]
      [   0   0   0   1   1   1   0   0   0   0   0   0   ]
      [   0   0   0   0   0   0   1   1   0   0   0   0   ]
      [   0   0   0   0   0   0   0   0   1   0   0   0   ]
      [   0   0   0   0   0   0   0   0   0    1   1   1 ]]

;

SC=
[[  1090  3510  2440  0  0  0  0  0  0  0  0  0  ]

[  0  0  0  2740  1020  3670  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2030  2400  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3480  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3430  2800  3530  ]]
;

AC=
[[[  1064  718  845  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  683  1018  1015  0  0  0  0  0  0  ]
```

```
[  0  0  0  0  0  0  791  1065  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  1098  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1028  780  800  ]]
[[  915  777  793  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  997  987  936  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  728  606  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  977  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  676  828  776  ]]
[[  695  1092  1043  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  690  898  933  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  669  672  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  602  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  927  1012  669  ]]
[[  600  977  968  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  800  696  933  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  813  738  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  1024  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  676  771  931  ]]
[[  1061  695  1067  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1053  638  736  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  738  806  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  694  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1044  887  779  ]]
[[  788  1099  864  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  616  1046  1098  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  894  857  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  847  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1006  789  677  ]]
[[  945  729  802  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  907  982  1078  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  772  957  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  898  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  621  788  847  ]]
[[  658  1031  879  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  823  797  1081  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  995  888  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  638  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  795  990  871  ]]
[[  903  675  805  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  703  971  940  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  1075  868  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  661  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  680  941  891  ]]
[[  953  995  710  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  770  781  697  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  623  874  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  738  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  624  949  974  ]]]

;
//
D=
[[    100   0     0     0     0     0     0     0     ]
[     0     100   0     0     0     0     0     0     ]
[     0     0     0     100   0     0     0     0     ]
[     0     0     100   0     0     0     0     0     ]
[     0     0     0     0     0     100   0     0     ]
```

```
[     0     0     0     0     0     0     0     100   ]
[     0     0     0     0     0     0     100   0     ]
[     0     0     0     0     0     0     100   0     ]
[     0     0     0     0     100   0     0     0     ]
[     0     0     0     0     100   0     0     0     ]]



;

UWC= [[     3     5     6     4     3     4     7     4     7     6     ]
[     3     7     5     7     6     3     3     5     6     4     ]
[     4     4     3     5     6     7     7     7     7     7     ]
[     5     7     7     7     5     7     7     5     3     3     ]
[     3     6     6     7     3     4     4     6     7     7     ]
[     4     5     4     7     6     3     4     4     3     4     ]
[     7     6     5     4     7     3     4     3     7     3     ]
[     4     3     4     4     3     3     4     5     6     4     ]]
;

LFT =[[     2     3     4     5     6     ]
[     3     0     4     5     6     ]
[     3     4     0     5     6     ]
[     4     5     0     0     6     ]
[     3     4     5     0     6     ]
[     3     4     0     5     6     ]
[     4     5     0     0     6     ]
[     4     5     0     0     6     ]
[     3     4     0     5     6     ]
[     3     4     5     0     6     ]]


     ;

LT= [ 6     6     6     6     6     6     6     6     6     6     ]


;

OP=[  0.52  0.60  0.66  0.40  0.59  0.46  0.33  0.29  0.75  0.75  ]



;

//CPR=[10 9 5 6 7 4 5 8 ];

R=[   0.72  0.52  0.37  0.61  0.32  0.84  0.68  0.36  0.37  0.38  0.58  0.62
      ]



;

FPC=
[[[  43  42  51  0  0  0  0  0  0  0  0  0  ]
```

```
[  0  0  0  58  63  74  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  51  53  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  54  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  55  65  50  ]]
[[  68  61  43  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  47  61  74  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  54  50  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  48  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  57  44  77  ]]
[[  56  59  54  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  50  80  67  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  49  67  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  56  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  79  50  63  ]]
[[  46  54  53  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  60  53  53  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  79  70  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  70  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  77  78  73  ]]
[[  68  61  43  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  47  45  73  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  61  42  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  59  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  41  65  52  ]]
[[  43  57  57  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  56  44  44  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  44  78  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  77  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  64  77  48  ]]
[[  55  48  75  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  51  64  77  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  53  53  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  62  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  63  66  53  ]]
[[  44  50  46  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  62  74  60  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  75  74  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  40  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  62  74  78  ]]
[[  42  76  43  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  60  40  44  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  44  52  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  79  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  45  52  58  ]]
[[  79  66  53  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  59  43  76  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  40  55  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  71  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  71  67  56  ]]]
;

UPC= [[  3  3  2  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  2  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  4  5  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  4  5  5  ]]
;
```

```
UPT= [[[  5  1  3  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3  2  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  1  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  4  2  1  ]]
[[  3  4  3  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  3  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  5  2  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  4  3  ]]
[[  4  2  4  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  4  4  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  1  4  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  4  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  5  5  5  ]]
[[  3  2  4  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  4  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  5  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  5  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3  2  4  ]]
[[  3  4  4  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  2  5  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3  5  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  4  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  4  2  3  ]]
[[  5  1  2  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  4  5  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  5  1  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  1  5  ]]
[[  5  5  2  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3  5  4  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  4  5  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  4  3  3  ]]
[[  1  5  5  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  2  1  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  4  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  4  3  3  ]]
[[  4  3  3  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  3  4  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  4  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  5  2  ]]
[[  2  4  4  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  5  5  1  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  5  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  4  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  2  3  2  ]]]
;

CAP=

[[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]
```

```
[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]]
[[  3003  3654  3192  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3664  3732  3885  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3166  3566  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3257  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3327  3240  3807  ]]
[[  3559  3900  3126  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3132  3271  3969  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3997  3390  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3404  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3139  3772  3237  ]]
[[  3759  3106  3450  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3689  3625  3737  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3923  3039  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3541  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3516  3407  3694  ]]
[[  3990  3332  3919  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3965  3092  3756  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3315  3342  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3403  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3225  3982  3049  ]]
[[  3251  3129  3848  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3479  3960  3148  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3460  3309  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3928  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3765  3808  3489  ]]
[[  3080  3016  3147  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3695  3505  3105  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3828  3599  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3500  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3578  3369  3441  ]]]
;

FTC=

[[  0  130  132  144  189  149  155  165  168  112  175  151  ]
[  0  0  159  154  145  126  136  199  178  138  112  138  ]
[  0  0  0  184  145  133  113  161  171  164  160  197  ]
[  0  0  0  0  135  176  119  148  182  152  118  175  ]
[  0  0  0  0  0  177  148  143  138  194  193  198  ]
[  0  0  0  0  0  0  107  164  194  199  105  132  ]
[  0  0  0  0  0  0  0  179  130  168  116  171  ]
[  0  0  0  0  0  0  0  0  186  187  101  119  ]
[  0  0  0  0  0  0  0  0  0  125  109  176  ]
[  0  0  0  0  0  0  0  0  0  0  153  115  ]
[  0  0  0  0  0  0  0  0  0  0  0  191  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]]
;

UTC=

[[  1  2  4  2  3  3  0  3  1  1  2  0  ]
[  4  3  0  1  5  2  0  2  4  4  1  1  ]
[  1  4  0  2  4  2  5  0  5  0  2  3  ]
[  5  4  5  4  3  4  5  2  0  1  2  5  ]
```

```
[   5   1   4   4   2   3   5   4   5   4   4   2   ]
[   1   4   1   3   3   4   1   2   2   4   3   3   ]
[   1   1   2   2   0   4   5   5   5   4   5   2   ]
[   4   5   4   2   0   1   1   0   0   0   2   5   ]
[   3   3   1   0   0   4   2   2   0   3   2   2   ]
[   3   2   5   0   2   2   2   4   5   5   3   3   ]
[   0   2   2   5   3   2   5   2   2   0   0   0   ]
[   3   2   2   1   5   1   4   2   0   5   3   1   ]]
;

TTC=
[[[     0       1       0       0       0       ]
[       0       0       1       0       0       ]
[       0       0       0       1       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]]
[[      0       0       1       0       0       ]
[       0       0       0       0       0       ]
[       0       0       0       1       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       1       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       1       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       1       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
[       0       0       0       1       0       ]
[       0       0       0       0       0       ]
[       0       0       0       0       1       ]
[       0       0       0       0       0       ]]
[[      0       1       0       0       0       ]
```

```
[     0     0     1     0     0     ]
[     0     0     0     0     1     ]
[     0     0     0     0     0     ]
[     0     0     0     0     0     ]]]
;

UW=

[[    3     6     8     2     8     2     4     2     2     6     ]
[     4     0     5     6     3     5     4     5     4     4     ]
[     8     3     0     0     4     0     0     0     0     6     ]
[     3     2     4     0     0     8     0     0     7     0     ]
[     6     5     8     4     5     7     6     3     8     3     ]]
;

HCS=

[[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  1  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  1  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  3  3  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  3  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  2  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  1  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  1  2  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  2  3  2  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  2  2  1  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  2  1  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  3  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  2  1  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  3  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  1  1  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  2  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  3  1  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3  1  1  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  1  2  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  3  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  2  1  1  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  1  1  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  1  2  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  1  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  3  2  3  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  1  1  1  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  2  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  1  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  1  3  3  ]]
```

```
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  3  1  3  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  2  1  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  3  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  3  3  1  ]]
[[  0  0  0  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  1  2  3  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  2  2  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  1  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  1  2  3  ]]]


;

HCF=
[[[  3  5  4  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  3  5  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  3  3  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  5  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  5  5  4  ]]
[[  3  5  4  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  5  3  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  3  3  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  5  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  3  3  4  ]]
[[  5  3  3  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  3  5  5  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  4  5  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  3  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  4  4  5  ]]
[[  3  5  5  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  4  3  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  4  3  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  5  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  4  5  5  ]]
[[  3  4  5  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  3  5  5  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  3  5  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  3  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  3  3  5  ]]
[[  5  4  4  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  5  5  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  4  5  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  5  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  5  5  3  ]]
[[  5  3  3  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  3  4  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  4  4  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  3  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  4  4  3  ]]
[[  3  3  4  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  4  5  4  0  0  0  0  0  0  ]
 [  0  0  0  0  0  0  5  3  0  0  0  0  ]
 [  0  0  0  0  0  0  0  0  4  0  0  0  ]
 [  0  0  0  0  0  0  0  0  0  5  4  4  ]]
[[  3  5  3  0  0  0  0  0  0  0  0  0  ]
 [  0  0  0  4  5  4  0  0  0  0  0  0  ]
```

```
[  0  0  0  0  0  0  5  3  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  5  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  5  4  3  ]]
[[  5  5  3  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  3  3  3  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  4  4  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  5  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  5  4  5  ]]]

;

TRCAP=

[[  0  0  0  573000  698000  345000  446000  632000  654000  416000  344000
637000  ]
[  0  0  0  608000  416000  400000  447000  362000  390000  678000  307000
526000  ]
[  0  0  0  432000  612000  422000  320000  519000  553000  490000  329000
624000  ]
[  0  0  0  0  0  0  358000  451000  353000  432000  555000  700000  ]
[  0  0  0  0  0  0  640000  470000  337000  328000  390000  376000  ]
[  0  0  0  0  0  0  519000  350000  656000  305000  361000  475000  ]
[  0  0  0  0  0  0  0  0  692000  301000  317000  653000  ]
[  0  0  0  0  0  0  0  0  573000  329000  689000  539000  ]
[  0  0  0  0  0  0  0  0  0  490000  513000  609000  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]
[  0  0  0  0  0  0  0  0  0  0  0  0  ]]
;

CDTRCAP=

[[  0  0  0  0  0  0  0  0  0  303546  322329  298202  ]
[  0  0  0  0  0  0  0  0  0  299667  219960  203908  ]
[  0  0  0  0  0  0  0  0  0  215799  300684  224484  ]
[  0  0  0  0  0  0  0  0  0  309866  237190  337052  ]
[  0  0  0  0  0  0  0  0  0  286376  321123  289253  ]
[  0  0  0  0  0  0  0  0  0  228721  210354  324244  ]
[  0  0  0  0  0  0  0  0  0  211718  207837  217869  ]
[  0  0  0  0  0  0  0  0  0  201287  245509  227398  ]]
;

CDTRCOST=

[[  0  0  0  0  0  0  0  0  0  6  7  7  ]
[  0  0  0  0  0  0  0  0  0  6  9  4  ]
[  0  0  0  0  0  0  0  0  0  6  8  8  ]
[  0  0  0  0  0  0  0  0  0  8  6  8  ]
[  0  0  0  0  0  0  0  0  0  5  5  9  ]
[  0  0  0  0  0  0  0  0  0  9  9  8  ]
[  0  0  0  0  0  0  0  0  0  9  8  3  ]
[  0  0  0  0  0  0  0  0  0  3  6  6  ]]
;
```