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Modelling resilience in supply chain

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Resumo

As cadeias de abastecimento globais são vulneráveis a inúmeras perturbações que podem afetar negativamente o desempenho operacional e financeiro das empresas. A capacidade das empresas em responder adequadamente às perturbações da cadeia de abastecimento, isto é, a capacidade de serem resilientes, é vital para se manter um elevado nível de competitividade, quer das empresas quer das respetivas cadeias de abastecimento. O propósito desta tese é a modelação da resiliência no contexto da cadeia de abastecimento. Mais especificamente, o objetivo consiste no desenvolvimento de um modelo explicativo da resiliência da cadeia de abastecimento e na modelação de índices de resiliência para avaliar a capacidade das empresas quanto à sua resiliência. Usando uma abordagem centrada na "construção de teoria", foi conduzida uma investigação suportada pelo método de estudo de caso em sete empresas pertencentes ao sector *upstream* da cadeia de abastecimento da indústria automóvel Portuguesa. Verificou-se que os gestores não associam as perturbações da cadeia de abastecimento a eventos específicos, mas sim aos efeitos negativos que estes provocam. O conjunto de práticas resilientes adotadas pelas empresas depende do tipo de perturbações e respetivos efeitos negativos, tendo-se constatado que os principais modos de falha que emergem do estudo de caso são "escassez de capacidade" e "escassez de material". A partir das evidências do estudo de caso foram propostas oito proposições, as quais foram utilizadas no desenvolvimento de um modelo explicativo das relações existentes entre perturbações, modos de falha e práticas resilientes da cadeia de abastecimento. Para sustentar a avaliação de resiliência das empresas, dois índices de resiliência foram modelados e desenvolvidos. Estes índices pretendem medir a capacidade das empresas em manter o seu desempenho em termos de "entrega no prazo" quando ocorre uma "escassez de capacidade" e/ou uma "escassez de material". Finalmente, os índices foram testados nas empresas. A dissertação contribui para a literatura existente ao investigar empiricamente os principais efeitos das perturbações na cadeia de abastecimento; por outro lado, abre perspetivas quanto à forma de aumentar a resiliência das empresas e, por conseguinte, das cadeias de abastecimento em que estão inseridas. Neste sentido, é proposta uma abordagem para avaliar a resiliência das empresas sendo identificado um conjunto de variáveis de estado da cadeia de abastecimento, as quais poderão ser monitorizadas com vista à melhoria da resiliência das empresas e das respectivas cadeia de abastecimento.

Termos-chave: Gestão da cadeia de abastecimento, Resiliência, Perturbação, Cadeia de abastecimento automóvel, Construção de teoria, Estudo de caso

Abstract

Global supply chains are vulnerable to a number of disturbances that may affect negatively company's operational and financial performance. The company's ability to cope with supply chain disturbances, i.e. the ability to be resilient, is vital to sustain the company and respective supply chain competitiveness. The aim of this thesis is modelling resilience in a supply chain context. More specifically, it is intended to develop an explanatory framework of the supply chain resilience phenomena and to model supply chain resilience indices to be deployed at individual company level. These indices intend to measure the companies' ability to be resilient in a supply chain context. Using a theory building approach, a case study was conducted in seven companies' belonging to the Portuguese automotive upstream supply chain. It was found that managers do not associate supply chain disturbances to a particular type of events, but with the negative effects that events provoke. When companies experience a disturbance, its ability to deliver on-time may be compromised. The resilient practices, adopted by companies, depend on the type of supply chain disturbances and their negative effects. The main failure modes arising from the case study are "capacity shortage" and "material shortage". Eight propositions were derived from the case study empirical findings. They were used to develop the supply chain resilience explanatory framework, to provide additional understanding regarding the relationships between supply chain disturbances, supply chain failure modes and resilient practices. To support the assessment of companies' resilience, two resilience indices were modelled and developed. These indices intend to measure the companies' ability to sustain its performance in terms of "on-time delivery" when a "capacity shortage" or "material shortage" occur. Finally, the indices were tested in companies belonging to the Portuguese automotive upstream supply chain. The dissertation contributes to the existing literature by empirically investigating the main effects of supply chain disturbances and how companies can increase supply chain resilience. It suggests an approach to assess companies' resilience and identifies a set of supply chain state variables that companies may control to improve supply chain resilience.

Keywords: Supply chain management, Resilience, Disturbance, Automotive supply chain, Theory building, Case study

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List of abbreviations and symbols

b - Length of the triangle

b1 - Damping time

b2 - Recovery time

EDI - Electronic data interchange

FGI - Finish goods inventory

h - Depth of the triangle

IT - Information technology

JIT - Just-in-time

JIT suppliers - Just-in-time suppliers

N_{zs} - Number of state variables contributing to minimize severity of failure mode z

N_{zr} - Number of state variables contributing to minimize the recovery time for failure mode z

OEM - Original equipments manufacture

R_{Cn} - State variable n that contributes to minimize the "capacity shortage" as well as "material shortage" recovery time

R_{CSl} - State variable l that contributes to minimize the "capacity shortage" recovery time

R_{MSm} - State variable m that contributes to minimize the "material shortage" recovery time

Resilience Index $_{CS}$ - Company resilience "on-time delivery" to "capacity shortage"

Resilience Index $_{MS}$ - Company resilience "on-time delivery" to "material shortage"

Resilience Index $_z$ - Resilience index for a failure mode z

S_{Ck} - State variable k that contributes to minimize the "capacity shortage" as well as "material shortage" severity

S_{CSi} - State variable i that contributes to minimize the "capacity shortage" severity

S_{MSj} - State variable j that contributes to minimize the "material shortage" severity

WIP - Work in process

X_{zs} - State variable s that contribute to minimize the severity of failure mode z

Y_{zr} - State variable r that contribute to minimize the recovery time for failure mode z

z - Failure mode type ("material shortage" or "capacity shortage")

1 Introduction

This chapter serves as an introduction to the dissertation. It covers the research aim, describing the motivation, objectives and research questions. It contains a brief description of the research methodology used in the research and it concludes with an outline of the dissertation structure.

1.1 Aim

In a global economy companies are no longer competing simply against each others but throughout the whole network of companies that are responsible to transform raw materials in final product and deliver it to the end users (Mills, Schmitz, and Frizelle, 2004). This network of entities responsible for different process, from materials production, components and products assembly, storage, transportation to delivery, is known as supply chain. The supply chain entities can be located in different geographic locations, e.g. a manufacturing plant located in South Europe can receive materials from local suppliers, but may receive materials coming from suppliers located in nearby countries or even different continents like Asia and America. Companies can supply products to customers that are spread around the globe and have to guarantee, at the same time, short lead times, high quality levels and low-cost. Therefore, it is critical to assure a smooth flow of materials between all the network entities. The management of the complex flow of materials and information between companies involve as well the coordination of the individual companies' processes, which is the heart of supply chain management (Mentzer *et al.*, 2001). Supply chain management is crucial for increasing companies' effectiveness as well as for enhancing competitiveness, customer service and profitability. Diverse supply chain management strategies like lean and agile are intended to reduce cost, through process improvements to reduce and eventually eliminate all "wastes" (non-value adding operations) and increase flexibility, i.e., developing the supply chain ability to rapid responding to changes in customer's demand (Christopher and Towill, 2000).

With supply chains crossing several countries and continents, transporting a multi-diversity of materials, from raw material to final product, events that create interruption of material flow, even if they happen in a remote place, can create large-scale disruptions. These disruptions may be propagated throughout the supply chain, causing severe negative effects in supply chains

compromising the ability to meet previously made commitments. Several companies, when subjected to disturbances occurrences, can not sustain the productivity level losing their competitiveness; therefore, the financial losses due to disturbances are growing significantly (Sheffi, 2005). The Japan earthquake in March 2011 is an illustrative example of how an unexpected event can affect global supply chains. We come across numerous media news describing this event negative outcome in companies and respective supply chains (Carvalho, Azevedo, and Cruz-Machado, 2012a). The automotive sector is referred to as one of the more affected by this event. The following quotations provide elucidative descriptions about the negative effects of this event:

- *"With some 500 parts firms affected in the quake and tsunami-devastated northeast, cutting off supply of electronic parts, resin-based products and more, Japan's auto industry is especially vulnerable to a ruptured supply chains"*[1]

- *"About 13% of worldwide auto output has been lost due to parts shortages and IHS Automotive has estimated it may cut output by as much as 30% within six weeks in a worst-case scenario."*[2]

- *"(...) there are 30,000 parts to build a car. We might see an impact on practically every production line in North America and most of Europe because of this supply interrupt, this black swan for the global auto industry in Japan"*[3]

The tendencies of many companies to seek out low-cost solutions, because of pressure on margins, may have led to leaner but more vulnerable supply chains (Azevedo *et al.*, 2008; Peck, 2005). As a result, supply chains are exposed to disruption and, in consequence, the risk to business continuity has increased. In a preceding research related to agile and resilient supply chains we argue that companies and supply chain competitiveness depend not only on the lowest-cost, higher quality, reduced lead time and higher service level; they should have the ability to avoid and overcome several disturbances that may jeopardize their performance, i.e., they should be resilient (Carvalho, Azevedo, and Cruz-Machado, 2012b).

The resilience seems to be, apparently, in conflict with an efficient use of resources in supply chain: the redundancies in resources and processes allow an increase in the system resiliency, but redundancies should be minimized to reduce operational cost systems. It seems that what can be

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[1] "Analysis - Japan car recovery may take months". Available at:
http://www.reuters.com/article/2011/03/25/uk-japan-quake-autos-idUKTRE72O1HZ20110328
[2] "Japan carmakers take steps in North America to fight disruption". Available at:
http://www.reuters.com/article/2011/03/30/business-us-japan-automaker-output-idUKTRE72T0M320110333
[3] "Japan could cause auto supply chain rethink: Expert". Available at:
http://www.moneycontrol.com/news/world-news/japan-could-cause-auto-supply-chain-rethink-expert_532800.html

good from the competitive point of view, can cause a disaster on crisis situations; it may be worst if the companies can not be resilient and robust enough to recover the loosed competitiveness. The ability to react appropriately to disruptions, whether natural or man-made, is a strategic necessity for business survival; this becomes more relevant when the company is a member of an interdependent network of entities (Hanna, Skipper, and Hall, 2010; Ponomarov and Holcomb, 2009; Sheffi and Rice, 2005). The creation of resilience attributes in companies, and therefore in supply chain, will contribute to enhance the supply chain performance and competitiveness.

Interest in supply chain disruptions and respective negative consequences has been growing in last years and the topic is become a main stream (Stock, Boyer, and Harmon, 2009). Whereas in the past the principal objective of supply chain design was cost minimization or service optimization, the emphasis today has to be upon resilience (Blackhurst, Dunn, and Craighead, 2011; Pettit, Fiksel, and Croxton, 2010; Ponomarov and Holcomb, 2009; Tang, 2006a). Resilient supply chains may not be the lowest-cost supply chains but they are more capable of coping with the uncertain business environment. The automotive supply chain is a typical example of high vulnerability levels to disturbances (Svensson, 2000). According to Thun and Hoenig (2011) the trends in globalization and the necessity to offer many products variants are the key drives to increase the vulnerability of this industry. Therefore, in the automotive supply chains the management focus should consider as well resilience and not only cost minimization.

The present thesis intends to study the supply chain resilience thematic. The research was integrated in two comprehensive research projects:

- "Lean, agile, resilient and green supply chain management" (funded by Fundação para a Ciência e Tecnologia - Project MIT-Pt/EDAM-IASC/0033/2008). The main objective of this project is to develop a deep understanding of the relationships required for the compatibility of lean, agile, resilient and green (manufacturing) in order to contribute to better production systems and supply chains.

- "Supply Chain Management: design for resilient systems" (funded by Fundação para a Ciência e Tecnologia - Project PTDC/EME-GIN/68400/2006). The main objective is to develop a management support system prototype to help managers to react quickly and efficiently to the effects of disruptions that can occur in a supply chain, sustaining a high service level to customers and to merge the necessary information to mitigate plans if the disruption became repetitive.

As a result of the participation in these projects we developed several research works within the supply chain resilience thematic. In particular, a number of papers were published and contributed

to the development of the resilience thematic in supply chain context (Azevedo *et al.*, 2012; Carvalho, Azevedo, and Cruz-Machado, 2012a; Carvalho, Azevedo, and Cruz-Machado, 2012b; Carvalho *et al.*, 2012; Carvalho, Maleki, and Cruz-Machado, 2012; Carvalho, Tavares, and Cruz-Machado, 2012; Carvalho *et al.*, 2011; Carvalho, Duarte, and Cruz-Machado, 2011). These works disclose the relevance of supply chain resilience thematic in academics, but also in managerial domains. However, it was found that there are still some research gaps that need to be addressed.

First, much of the existing research is focused on the question on "why the companies are vulnerable to supply chain disruptions" (Peck, 2005; Svensson, 2000; Wagner and Neshat, 2010). However, it is increasingly clear that companies need to deal with supply chain disruptions no matter if they are more or less vulnerable. The Japan earthquake in March 2011 is an example of how an unexpected event can affect global supply chain. Second, the development of the field tends to focus on anecdotal studies and there is a lack of empirical evidences on how companies can improve the resilience of the network where they are inserted. Blackhurst *et al.* (2005) state that there is a limited amount of information on how to deal with supply chain disturbances from a practical point of view, in both the short and the long term.

A high level of analysis of disruptions in supply chain, generally focused in uncertainty, risk perceptions and hazards, might prevent the "drilling down" of key variable and relationships among them and prevent the development of new methodologies to manage these issues (Blackhurst *et al.*, 2005). As state by Hintsa *et al.* (2009), in the supply chain security context, the academic research community has a clear mission to bridge the gap between theoretical supply chain security studies, emerging security standards and practical managerial actions. One way of doing it is to proceed with pragmatic case studies on supply chain models in the context of real world supply chains.

Recent studies have highlighted the importance to quantify the supply chain ability to overcome the negative effects of disturbances. In this line, Ponomarov and Holcomb (2009) argue that measurement of supply chain resilience represents a future potential research stream; such measurement would assist companies and their respective supply chain's to determine the extent to which elements and components of supply chain resilience should be developed. Pettit, Fiksel and Croxton (2010) also propose a conceptual supply chain resilience framework to define resilience in terms of measurable capabilities factors. According to them, the best level of resilience will be achieved only when a balance is maintained between capabilities and vulnerabilities. However, they do not specify how to assess the companies' ability to avoid or to minimize the negative effects of supply chain disturbances, i.e., how to assess companies' resilience in a supply chain context. In a previous research we propose a hierarchical index to measure automotive companies' and supply chain level of greenness and resilience (Azevedo *et al.*, 2012). It was considered that the supply

chain resilience level depends on a set of seven resilient practices that reflects the company ability to cope with unexpected disturbances. The resilient practices were selected using evidences from literature and experts knowledge, but no explanatory framework was developed. In parallel with the development of resilience measures, Wagner and Neshat (2010) propose a novel approach based on graph theory to quantify and mitigate supply chain vulnerability. Recently, the same authors perform an empirical study to compare supply chain vulnerability indices of different firms (Wagner and Neshat, 2012). Moreover, these authors stress out the need to address measurement and implementation issues in supply chain resilience context.

1.2   Objective and research questions

While the existing research is valuable, models to support supply chain resilience management are needed. In particular, the issue on "how to assess the supply chain resilience" still has no answer. Therefore, this dissertation purpose is modelling resilience in a supply chain context. Namely, the objective is to develop theory that can be used to support the assessment of supply chain resilience of a company. To attain this objective it is necessary to develop an explanatory framework that capture all the relevant variables describing the supply chain resilience phenomena and clarifying the pathways by which supply chain resilience should be addressed. More specifically, the objectives are:

- To propose a supply chain resilience assessment model.

- To propose an framework for supply chain resilience modelling.

- To model indices to assess company's supply chain resilience.

In a first step, it is necessary to understand how companies manage their processes within a supply chain context and characterize the main supply chain management practices deployed by companies. In particular, the identification of resilient practices used to avoid or minimize the disturbance negative effects is crucial for a better understanding of the resilience phenomena. The following research questions are addressed:

1. Which practices companies deploy to manage their supply chain? What are the consequences of those practices on supply chain performance?

2. What is a supply chain disturbance? How managers perceive the effects of a supply chain disturbance?

3. How the supply chain disturbances affect the company's performance? And why companies do not sustain their performance level when a disturbance occurs?

4. Which resilient practices companies deploy to avoid or minimize the negative effects of the supply chain disturbances?

1.3 Methodology

The research methodology comprises two main research phases as illustrated in Figure 1-1. Since there are few theoretical developments in the supply chain resilience field, the research adopts an explorative character. A theory building methodology based on case studies was selected. In a first research phase, a case study is developed to understand the effect of disturbances on supply chains and how companies overcome its negative effects.

The field work was focused in the automotive supply chain, namely in the upstream supply chain taking into consideration the dyad manufacture – 1st tier suppliers and logistic service providers. From this case study an empirical data platform emerged to identify the critical components describing supply chain resilience phenomena.

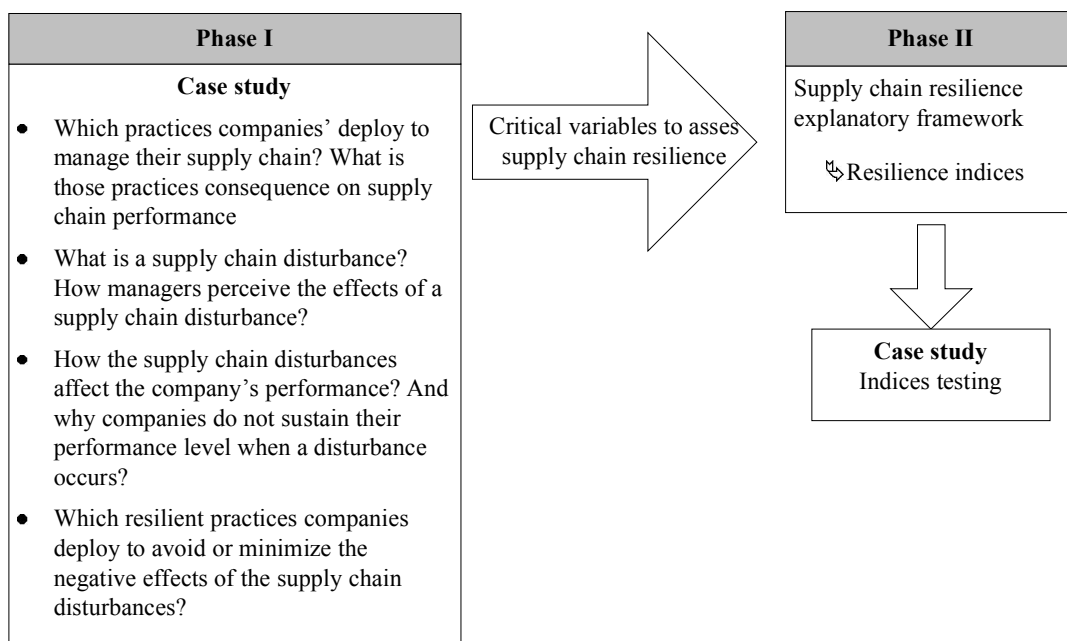| Phase I		Phase II
Case study	Critical variables to asses supply chain resilience	Supply chain resilience explanatory framework
• Which practices companies' deploy to manage their supply chain? What is those practices consequence on supply chain performance		⇨Resilience indices
• What is a supply chain disturbance? How managers perceive the effects of a supply chain disturbance?		**Case study** Indices testing
• How the supply chain disturbances affect the company's performance? And why companies do not sustain their performance level when a disturbance occurs?		
• Which resilient practices companies deploy to avoid or minimize the negative effects of the supply chain disturbances?		

Figure 1-1 Research methodology overview

To obtain more theoretical insights, a second descriptive phase was designed: an explanatory framework with the identification of supply chain resilience variables and respective relationships was developed. Therefore in this dissertation the proposed framework is data driven and not pure

theory driven, i.e., the main variables describing the resilience phenomena emerge from empirical data. Using this framework, two supply chain resilience indices are modelled. Finally the indices were tested using a case study approach.

Since the supply chain resilience thematic covers a large scope of research topics including vulnerability, supply chain risk, organizational structure, among others, in this dissertation the focus will be on the companies' behaviour and how they overcome the negative effects of supply chain disturbances keeping the focus on company's supply chain. Another delimitation of this dissertation is related to the type of supply chain under study: the empirical work will be focus on a Portuguese automotive upstream supply chain.

1.4   Contents

The thesis results from theoretical and methodological explorations within the scope of supply chain resilience. In Figure 1-2 the organization of the thesis is presented, highlighting the theoretical, methodological and empirical steps used to reach the thesis results.

This thesis consists of seven chapters. The first one introduces the thesis underling motivation and main objectives. In the second and third chapter, the relevant literature on supply chain resilience is enfolded to provide clarifications regarding the research thematic. In Chapter 2, the topics related to supply chain management, supply chain performance, disturbances, failures modes and resilience are discussed. This chapter contains a review of main supply chain management practices and performance measures found in the literature. In addition, it provides an overview on supply chain disturbances and failure modes and the identification of supply chain resilient practices. The chapter is concluded with the characterization of supply chain resilience using the "resilience triangle". In Chapter 3 the lean, agile and resilient practices are studied in detail, their attributes are identified and related to these management strategies. Moreover, a relevant set of supply chain resilient capabilities are identified. The design for supply chain resilience is also explored. The chapter concludes with a conceptual model for supply chain resilience assessment.

Chapter 4 introduces the research methodology used in this thesis and the main research options are discussed and justified. The utilization of a theory building approach using a case study method to attain the research objectives is justified. The criterion for case selection is discussed. The chapter contains data collection and analysis procedures, along with the design criteria used to assure the case study quality. This chapter supports the case study findings described in Chapters 5 and 6.
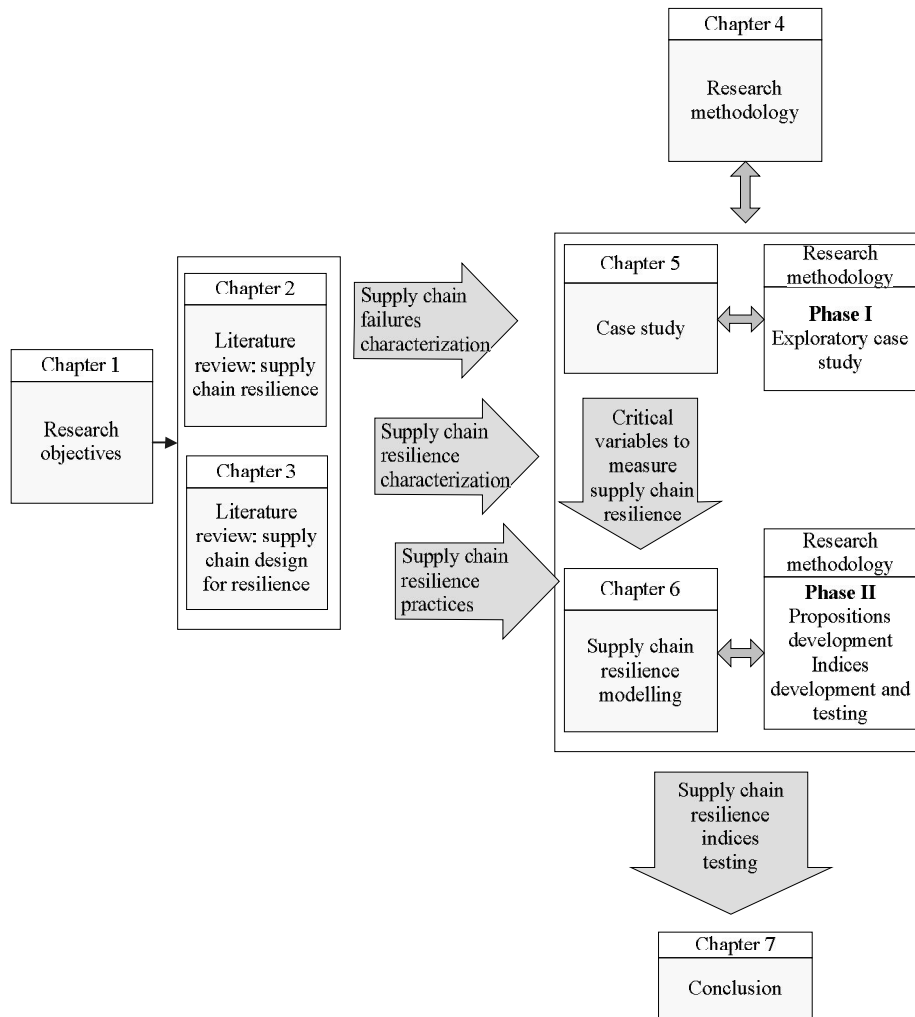
Figure 1-2 Organization of the thesis

In Chapter 5, the data collected in research Phase I of the case study will be presented. The chapter begins with a detailed description of the studied sample; the main supply chain management practices used by companies in the sample are identified. Supply chain disturbances and failure modes are identified using empirical evidences collected in the case study. The chapter terminates with the identification of main practices used by companies to overcome the disturbances negative effects.

Chapter 6 presents the theory derived from the case study findings. A framework for supply chain resilience modelling and respective propositions is proposed using results from research Phase I and literature enfolding. Using this explanatory framework, two supply chain resilience indices are modelled; their application is illustrated in a case study setting.

Finally, Chapter 7 provides a general discussion in theoretical, methodological and empirical issues relevant to supply chain resilience thematic. The chapter finishes with the main conclusions of the thesis and future work proposals.

The thesis includes relevant references about supply chain resilience and others supporting topics, e.g. supply chain management, supply chain vulnerability, security and disruption, along with lean and agile supply chain strategies. The literature reviewed follows a purposive sample of articles, i.e., the literature included in this thesis was based on central and pivotal articles published in the top journals in the field. In addition, four annexes, containing the interview protocols, and one example of a technical report, to support the case study development, are included.

1.5   Conclusion

This chapter provides an overview of the dissertation. The justifications of the research topic as well as the objectives were discussed. The dissertation presents a research on supply chain resilience: it explores how companies overcome the negative effects of disturbances and how they can improve their resilience. The methodology comprising two research phases is brief described. With all the important areas of the research briefly introduced in this chapter, the following six chapters of this dissertation will present a detailed description and findings of the research topic.