Robust Food Supply Chains

An integrated framework for vulnerability assessment and disturbance management

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Thesis

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1. General introduction of the research project

Jelena V. Vlajić

"Robust food supply chains, An integrated framework for vulnerability assessment and disturbance management", PhD Thesis, Wageningen University

“Intellectuals solve problems, geniuses prevent them."

Albert Einstein (1879-1955)

Years of emphasis on efficiency and cost reduction (Christopher and Lee, 2004) has resulted in less slack in operations, compressed cycle times, increased productivity and minimized inventory levels along supply chains (SC). Combined with tight tolerance settings for logistics and production processes, SCs are becoming increasingly vulnerable to disturbances in their processes. The presence of disturbances in logistics and production processes may result in non-robust performances (Kleindorfer and Saad, 2005), which can decrease the competitive power of the entire SC in the market.

Supply chain management (SCM) literature suggests that the susceptibility level of SCs to disturbances is industry dependent. Research findings based on a large-scale survey conducted in Germany (Wagner and Neshat, 2010) show that the food and consumer goods industry is fairly vulnerable: more than some industries (e.g. engineering industry) and less than other types of industries (e.g. automotive and ICT). Due to multiple timing constraints, information requirements and return flows in general (van der Vorst, 2000), managing any food SC is inherently difficult (Roth et al. 2008). The fresh food products SC brings its own set of challenges (Apte, 2010) because of stricter timing and product quality constraints. This is especially noticeable in efficient food SCs that are very concerned with expected on-time delivery (Murphy and Hall, 1995), i.e. reliability of delivery in a defined time window and high product quality.

Delays are especially harmful for fresh food products because they may decrease their shelf life and jeopardize product quality. For example, in large retail systems such as *Wal-Mart* in U.S.A. (Apte and Viswanathan, 2000) and *Albert Heijn* in the Netherlands (de Koster, 2002) fresh food products are typically cross-docked in the distribution centre (DC), and stored only over a period of two to three hours. An inbound transport delay of an hour or more can seriously disrupt cross-docking operations because it requires fast rescheduling of internal material handling operations, such as task assignments for forklift drivers and unloading locations for trucks in the receiving area. Otherwise, trucks designated for outbound transport will wait longer than planned for loading and the entire delivery process might suffer from non-robust performances. Moreover, as fresh food products are usually replenished on a daily basis, and one truck might visit multiple retail outlets, a missed or seriously delayed delivery may cause chain of delays and thus negatively affect performances of the retail system: potential stock-out might result in lost sales, delivered products will have a shorter shelf life, and their quality might be damaged. In the interesting case of major grocery cross-docking DC in London, McKinnon et al., (2008) reported that an average of 46 out of 530 (8.7%) inbound deliveries were out of the 15-minute tolerance window of specified time for various reasons: traffic congestion, the poor reliability of agency drivers, vehicle break-downs and delays at previous delivery points on multiple-drop rounds.

Disturbances related to the quality of food products are subtle, but very important characteristics of food SCs. End customers demand high quality food products, and as stated already food production and retail typically have tight tolerances, which often result in food write-offs if there is only slight damage to the food product or its package. In Europe, a large percentage of fresh food products is written-off along the way due to quality-related problems. Grey fields in Table 1.1 show that fruit and vegetables have large write-offs in the stage of agricultural production and distribution, while meat has a large write-off in the processing and packaging stage (next to large losses in consumption).

Table 1. 1. Weight percentages of food losses and waste in relation to input in various SC stages, Europe (source: Gustavsson et al., 2011)

Product	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution: Supermarket Retail	Consumption
Fruit and vegetables	20%	4%	2%	12%	28%
Meat	3,5%	1%	5%	4%	11%

According to Chan et al., (2006), more than 80% of the product damage that occurs in international SC results from improper handling. Moreover, fresh food products are highly sensitive to pressure, which often causes write-offs and associated costs for the SC. Though modern SCs use pallets and material handling equipment that reduce the probability of product damage, in many SCs some handling operations are still manual, which contributes to increased vulnerability of the food SC. For instance, research results of FReLECTRA (2002) show that fresh fruit and vegetable products may be lifted and dropped on average between five to ten times between harvest and consumption. Experiments show that 15 % of apples in the third layer of the carton are bruised after dropping the carton from a 30-cm height and even 85% if the carton is dropped from a 120-cm height. After a journey of 1600 km and six handling operations the average proportion of bruised apples in tray packs is 10 - 15%. The subtle problem here is that bruises on the apples will not show up immediately, but up to two days later. In practical terms that means that, for example, 10-15% of apples sourced from Spain, which we buy in a supermarket in Wageningen (the Netherlands) might show bruises while they are in the supermarket (so these apples will be written-off by retailers) or even when we get them back home, at which point we might throw them away. Similar effects of improper handling can be observed in other types of fruits, such as bananas, as well as meat. The quality of bananas for example may even deteriorate fast due to temperature changes (e.g. bananas get brown stripes due to chilling injuries, or they may look cooked when exposed to high temperatures). Meat can be written-off during processing as well due to bruising, which results from improper handling of live animals in transport, or due to spoilage which results from exposure to higher temperatures. In any case, there is financial damage for all participants, as well as significant food waste.

As we indicated with previous examples, despite the efficiency of an industrialized food SC, complexity that results from characteristics of food product and processes makes it difficult to map this SC, and understand and analyze it so as to rectify its vulnerabilities (Apte, 2010). Hence, in general there is increasing interest among practitioners and academics to assess the level of food SC vulnerability, identify underlying causes and find ways to manage disturbances in order to achieve robust performances.

After highlighting SC vulnerability and the need for designing robust SCs from a practical perspective, in Section 1.2 we introduce the research problem and objective of the project. In Section 1.3 we present research questions, in Section 1.4 we describe the research design and methodology and in Section 1.5 we present outline of the research.

1.1. Research problem and objective

Literature provides many definitions of SCs, but in general it can be said that a SC is a group of actors that perform specific roles and processes linked to each other via goods, information and money flows, using specific infrastructures aiming to fulfil consumer wishes at the lowest cost (van der Vorst, 2000). Since 2000, in SCM literature, many authors refer to the SC as a supply chain network[1] (SCN) (cf. van der Vorst et al., 2005). The SC is only as strong as its weakest link (Svensson, 2000; Kleindorfer and Saad, 2005; Slone et al., 2007), which implies a need to consider vulnerability and robustness issues at the level of its actors, i.e. focal companies of SCs.

As the examples from practice show, SC performances depend to a large extent on the characteristics of the products (e.g. perishability), SC design (e.g. cross-docked

[1] Further on in the text, the terms (food) SC and (food) SCN will be used interchangeably.

product flows) and strictness of customer requirements (e.g. timing of deliveries, and product quality), as well as characteristics of SC environment (e.g. traffic congestions). All of these characteristics contribute to the emerging uncertainty in decision making process in SCs. According to van der Vorst (2000), SC uncertainty refers to decision making situations in the SC in which the decision-maker lacks effective control actions or is unable to accurately predict the impact of possible control actions on system behaviour because of a lack of: information (or understanding) of the environment or current SC state; a consistent model of the SC presenting the relationships between SC redesign variables and SC performance indicators. In our view, uncertainty may cause disturbances[2] to logistic processes. If not properly managed, disturbances result in food SC *vulnerability* (cf. Tang, 2006a). The degree of SC vulnerability is opposite to the degree of SC robustness.

SCM literature indicates a need for food SCs that will continue to function well even in the event of disturbances. To achieve this objective, i.e. sustaining SC robustness in all working conditions, the right strategies for managing disturbances have to be selected and implemented. As it will be shown in the literature review in Chapter 2, to achieve robustness and to remain competitive, SCs need an appropriate methodology to design and evaluate the required robustness in SCs or its counterpart – SC vulnerability. A decision-support method that helps managers to evaluate the vulnerability of their SCs can considerably increase the robustness of these chains (cf. Deleris and Erhun, 2005; Huaccho Huatuco et al., 2010).

The *research objective* considered in this PhD thesis is twofold:

1. *to contribute to SCM theory by developing a structured approach to assess SC vulnerability and improve performance robustness of the food SCs;*

2. *to help companies in the food industry to evaluate their current state of vulnerability and improve performance robustness by acquiring a better understanding of vulnerability issues.*

[2] In this thesis, we use "disturbances" as a generic term; in the SC literature, the terms disruptions, interruptions, and perturbations are also used in the same context.

1.2. Research questions

The term "robust" has been used in operations management and operations research literature since the 1960s (see Gupta and Rosenhead, 1968). Since then, it has also frequently been used in many other disciplines, such as statistics (e.g. McCaskey and Tsui, 1997), systems theory (e.g. Gribble, 2001; Carlson and Doyle, 2002), environmental sciences (e.g. Anderies et al., 2004; Gallopin, 2006), simulation (e.g. Law and Kelton, 2000; Kleijnen, 2005; Hennet and Mercantini, 2010), engineering (e.g. de Neufville, 2004; Esterman and Ishii, 2005) and social sciences (Jen, 2005).

In general, robustness is primarily related to the property of an object in the sense of its strength and fragility when the object is exposed to various conditions in its environment. This idea of robustness is used in SCM literature too. In context of SC, the term *robustness* is mainly connected to strategic problems of SC configuration in an uncertain environment (Santoso at al., 2004; Goetschalckx and Fleischmann, 2005) or to a severe disturbance of the SCN (Snyder, 2003; Bundschuh at al., 2003; Dong, 2006). Here, many authors broadly state that robust SCs should carry out their functions amid uncertainty and disturbances (e.g. Dreo et al., 2006; Dong and Chen, 2007). As we will show later, the issues and importance of SC robustness are not considered much for problems at a tactical and operational level. In the available literature, there is no clear and explicit definition of robustness in an SC context generally, or in food SC, as far as it is known to the author of this work. Therefore, based on the extensive literature survey conducted in 2007, we attempt to answer the first research question in Chapter 2:

RQ1: *What are the main research challenges related to (food) SC robustness?*

In SCM literature, scattered works that tackle issues of robust SC design can be found. First, in most of the papers the design of robust SCs is not even a central issue (e.g. see Ferdows, 1997). Second, many authors focus only on a particular problem: e.g. SC planning (Van Landeghem and Vanmaele, 2002); network design under serious disturbances (Mo and Harrison, 2005; Dong, 2006; Gaonkar and Viswanadham, 2006), or strategies in times of crisis (Simchi-Levi et al., 2002; Tang, 2006, 2006a). Third, some authors consider only a narrow domain, e.g. production systems (Asbjørnslett and Rausand, 1999). Therefore, as we will also show with other supporting literature in Chapter 3, an integrated framework to support the analysis and design of the SC that would result in robust performances is lacking. Hence, in Chapter 3 we provide an answer to the second research question:

RQ2: *What are the main elements that have to be considered in the design of robust SCs and what are the relationships between these elements?*

In both theory and practice there is a growing interest in disturbance prevention and management response principles that can be used to achieve robust SCs. One stream of a research is focused mainly on disturbances and their characteristics and categorization (e.g. Svensson 2000; Christopher and Lee, 2004; Christopher and Peck, 2004; Blackhurst et al. 2005; Peck, 2005; Viswanadham and Gaonkar 2008; Stecke and Kumar 2009) and the other stream is mainly focused on response concepts and principles in general (e.g. Simchi-Levi at al. 2002; Christopher et al., 2006; Hopp, 2008), or the effects of particular redesign strategies used (e.g. Tomlin, 2006). Literature suggests that the use and appropriateness of these principles is probably contextual, and that it depends on product and process (van der Vorst, 2000; Lunning et al., 2011), SC (Wagner and Bode, 2006) and SC environment (Jüttner, 2005) as relevant contextual factors. However, not much research has been devoted to investigating the relationship between characteristics of contextual factors and the use of the disturbance management principles (Manuj and Mentzer, 2008) in food SCs. Therefore, we attempt to answer the third research question in Chapter 4:

RQ3: *What is the relationship between the contextual factors of food SCs and the use of disturbance management principles?*

Due to the complexity of SC design, successful disturbance management is not possible without an adequate decision support system, as a tool for SC analysis, design and control. The literature indicates several modelling approaches that can be used for the design of a robust SC.

A large part of the research covers robust optimization models, which are used to solve and analyse the impact of uncertainty or disturbances on the SC level, e.g. supplier failures (Bundschuh at al., 2003), or location problems (Snyder, 2003), network configuration problems (Mo and Harrison, 2005), as well as on the tactical level, e.g. production planning (Wu, 2006; Leung at al., 2007), fleet planning (List at al., 2003), etc. These papers are mostly related to an analysis of solution robustness of defined performance(s)[3] and/or to an analysis of model robustness, and as such, they are not very applicable for the analysis of real SC problems related to disturbances. Other methods include Failure Modes and Effect Analysis (FMEA) (Scipioni et al., 2002; Sinha et al., 2004; Tuncel and Alpan, 2010), SC Event Management (SCEM) (Mentzer et al. 2001; Otto, 2003; Christopher and Lee, 2004; Waters, 2007), Simulation (Kleijnen and Smits, 2003; Saad and Kadirkamanathan, 2006; Melnyk et al., 2009; Hennet and

[3] Usually only financial performances are considered.

Mercantini, 2010), and graph theoretic approaches (Wagner and Neshat, 2010), i.e. network models, like Critical Path Methods (CPM) (Herroelen and Leus, 2004).

According to Blackhurst et al., (2005), Kleindorfer and Saad (2005) and Melnyk et al., (2009), a modelling methodology to understand how disturbances will affect a SC, and how far reaching the effects will be, is lacking in the current literature. This is supported by Wagner and Neshat (2010) who state that SC managers still need to be better equipped with methods for measuring SC performances when and after disturbance occurs, i.e. methods that would help companies to manage disturbances. Therefore, the fourth research question is:

RQ4: *How to systematically assess the impact of disturbances in SC processes on the robustness of (food) SC performances?*

1.3. Research design – methodology

Considering the nature of the main research questions (*what* and *how* questions), it is appropriate to use qualitative and quantitative methodologies with the support of adequate literature. For advanced research in areas of logistics and SCM it is necessary to use both – a combination of qualitative and quantitative methods (Meredith, 1998) and a combination of inductive and deductive approaches (cf. Mangan at al., 2004). Moreover, Meredith (1998) states: "qualitative and quantitative research methods are not mutually exclusive and, if combined, can offer even greater potential for enhancing new theories than either method alone". McCarthy and Golicic (2002) also point out that qualitative and quantitative methods can be combined "to determine the relational and operational factors that need to be in place as well as any moderators or mediators to the process". For example, successful combination of both methodologies is used to develop "Quick Scan" approach as a part of a generic methodology for the identification of change management opportunities in the SC (Naim et. all, 2002). To complete this project, we used different methodologies, both qualitative and quantitative.

In general, a *literature search* is used to find a research gap and formulate research questions. According to Strauss and Corbin (1998), there is also a need to return to the literature after data collection and analysis to confirm the findings. Therefore, we also used the literature to validate our findings, support their generalizability and indicate research limitations (Yin, 1994) and highlight further research directions.

Within this project, *case studies* are used for answering WHAT and HOW research questions for the purpose of:

- Exploration, which we used in
    a. Chapter 3, to identify main research challenges in practice in relation to robustness and vulnerability;
    b. Chapter 4, to identify characteristics of contextual factors for food SCs and disturbance management principles;
    c. Chapter 5, to identify relevant characteristics of food SCs that must be captured by simulation model.
- Testing, which we used in
    a. Chapter 3 to validate the research framework;
    b. Chapter 5 to validate the new vulnerability assessment method (VULA).

Initial insights into robustness and vulnerability issues relevant for the food industry are obtained from the meat industry, due to participation in the *EU FP6 project Q-porkchains*. The meat industry is selected because of its importance for the food industry, and human nutrition. Moreover, fresh meat is highly perishable and high safety standards apply, hence disturbances may have great impact on SC vulnerability. Based on the increased vulnerability of meat processors (e.g. see percentage of input rejected after shipment is received, Table 1.1) in the meat chain, we selected a processing company in the Netherlands as a case study. To test the research framework (Chapter 3) and capture the relevant characteristics of meat SCs to build a simulation model (Chapter 5), we performed data collection in the period from September 2008 to September 2009. Data sources used are: available reports, observations, as well as semi-structured interviews with the company directors and the operations and logistics managers. The data obtained was validated and checked with insights obtained in an earlier broader case study of the European meat SCs (cf. Wognum et al., 2009).

To extend the generalizability of our findings, we conducted separate case study research on food SCs in Serbia. To define the domain of the findings, based on expert opinions and data provided by the *Serbian Chamber of Commerce*, Belgrade we selected a population of large retail SCs. We used theoretical sampling to select cases from the population, as suggested by Eisenhardt (1989). As representative cases, we selected three SCs of leading companies in the retail sector, focusing on fresh fruit and fresh meat. These companies had been extending their business in the last few years at a time of global economic crisis (by opening new outlets and distribution centres) and therefore they can be considered as successful businesses that manage disturbances effectively.

In Table 1.2 we present an overview of the methods we used to answer the defined research questions.

Table 1. 2. Methodological design

Research question	Method	Outcome/Findings
RQ1.	Literature search on robustness issues.	Overview of definitions and perceptions on robustness. Overview of research challenges.
RQ2.	Literature search on elements that influence design of robust food SC	Research framework for design of robust SCs
	Open and semi-structured interviews with domain experts.	Overview of relevant components for the framework for design of robustness food SCs
	Exploratory case study	Tested framework
RQ3.	Literature search on contextual factors relevant for food chains and disturbance response principles	Research framework for investigation of relationships between contextual factors and disturbance response principles
	Exploratory case studies	Tested framework Propositions
RQ4.	Literature search on:	
	- modelling approaches for analysing the impact of disturbances on food SC performances and assessing vulnerability level of food SC	Proposition of a new method for vulnerability assessment (VULA method)
	- performance measures to assess food SC vulnerability	Vulnerability Performance Indicators (VPIs) Vulnerability Index (VI) Vulnerability profile and response matrix
	Exploratory case study based on: - Open interviews with logistic managers - Field visit - Historical data on daily profits Simulation modelling and scenario analysis	Application of the VULA method

1.4. Outline of the thesis

This thesis is organised as follows.

In Chapter 2 we answer RQ1: *What are the main research challenges related to (food) SC robustness?* Based on the methodology presented in Table 1.2, we present a classification of definitions and key elements used to define robustness in the context of SCs. These key elements will be used as a basis for Chapter 3.

In Chapter 3 we answer RQ2: *What are the main elements that have to be considered in design of robust SCs and what are relationships between these elements?* In this chapter, we first define SC robustness, and then we identify the main elements needed to achieve robust performances. By structuring them together we form a framework for the design of robust SCs. To verify its applicability, the research framework is tested on the meat SC. The methodology used to answer RQ2 is presented in Table 1.2.

In Chapter 4, we answer RQ3: *What is the relationship between the contextual factors of food SCs and the use of disturbance management principles?* Using the methodology presented in Table 1.2, we identify relevant contextual factors and disturbance management principles. Our findings show the relationship between them, and the dominant disturbance management principles used in retail SCs.

In Chapter 5 we answer RQ4: *How to systematically assess the impact of disturbances in SC processes on robustness of (food) SC performances?* We present a new method for vulnerability assessment, the VULA method, paying special attention to specific Key Performance Indicators (KPIs) used to assess vulnerability during and after disturbances.

In Chapter 6 we present a general discussion and give an overview of our findings, theoretical contributions, managerial implications, research limitations and directions for future research.

2. On robustness in food supply chain networks

This chapter is based on the article published as a book chapter:

Vlajic, J.V., van der Vorst, J.G.A.J., and Hendrix, E.M.T., (2010).

"*On robustness in food supply chain networks*",

in: "*Towards effective food chains*", Eds: Trienekens et al., Chapter 3, Wageningen Academic Publishers, The Netherlands, pp. 63-82;

ISBN 978-90-8686-148-4; DOI: 10.3921/978-90-8686-705-9.

In this chapter we answer Research Question **1**:

What are the main research challenges related to (food) SC robustness?

Abstract

Today's business environment is characterized by challenges of strong global competition where companies tend to achieve leanness and maximum responsiveness to customer demand. Lean supply chain networks (SCNs) are vulnerable to all kind of disruptions. For food SCNs, due to their inherent characteristics on the one hand and increased level of complexity, dynamics and uncertainty on the other hand, this vulnerability is even stronger. Therefore, methods are needed to design food SCNs in a robust way, i.e. they should be able to continue to function in the event of disruption as well as in normal business environment.

We conducted a systematic search in scientific literature up to 2008, also including books, monographs, doctoral theses and working papers. We searched in databases Scopus, Scirus and Google Scholar and defined the relevant keywords and criteria for article selection. Next, we performed content analysis of all selected articles. The main criterion for article selection was a definition or explanation of the word 'robust' or 'robustness: In the end we selected 60 publications of which 35 publications were related to supply chain management (SCM) issues.

This chapter presents a new overview of the current state of understanding regarding the concept of robustness. A review is given of how the concept of robustness is perceived in scientific literature and how it is modelled. Focus is on the FSCN context, but due to available literature we also explore neighbouring fields. We conclude that SCN robustness should be more precisely defined and related to certain business key performance indicators (not only to financial ones) to guide SCN improvement programs. Next to that, there is a need for a systematic overview of (re)design strategies that may improve SCN robustness (and considers all elements of SCN design) and a list of appropriate criteria to support the selection of the right strategy in a specific case.

Keywords: robustness, vulnerability, supply chain management, network design, modelling, food supply chain

2.1. Introduction

Today's business environment has become an international playing field in which companies have to excel in logistical performance, i.e. markets require full responsiveness and high reliability of supply at the lowest cost. Therefore, supply chain (SC) networks have eliminated most non-value adding activities and have become leaner. As a consequence, levels of uncertainty, dynamics and complexity increased (cf. Childerhouse and Towill, 2004). Lean SCs are more vulnerable to unanticipated events (disturbances), which means that their performance varies (Dong, 2006). Food SC networks are perceived especially vulnerable due to their dependence on natural processes (e.g. growth and quality change of products, seasonality). Designing SC networks in a robust way diminishes dependence of performance on uncertain events. The question here is, *what is robustness exactly; how is it perceived in literature and how can it be modelled such that one can evaluate and design robust (food) SCs*?

Robust and *robustness* as terms are frequently used in the literature. However, there is no general, widely accepted definition of robustness (Arndt and Müller-Christ, 2005). In general, the terms robust or robustness are:

- frequently related or interchangeably used with other terms;
- used at different levels of abstraction and for different purposes;
- defined in many ways, depending on the specific context (Bundschuh at al., 2003);
- used in various research areas, e.g., natural, technical or social sciences (see Jen, 2005).

The purpose of this chapter is to review literature on the concept of robustness, specifically from a SC network perspective. However, we also scan neighbouring literature to get insight in its perception and how it can be modelled.

This chapter is organized as follows. In Section 2 we embed the robustness issue in today's business environment from the perspective of SC network design. Section 3 describes the approach followed for a systematic literature research. In Section 4, we summarize and classify definitions of robustness found in the literature. In Section 5 conclusions and outlines for further research directions are given.

2.2. Robustness and Supply Chain Networks

We focus on how uncertainty, flexibility and robustness play a role in SC networks. A SC is a network of facilities that performs the functions of procurement of material, transformation of material to intermediate and finished products, and distribution of finished products to customers (Lee and Billington, 1993). Due to an increasing number of suppliers and customers and the variety of relationships between them, the SC has become a complex network. Since 2000, in supply chain management (SCM) literature, many authors refer to the SC as SC network (cf. van der Vorst et al., 2009). Characteristics of SC networks are product and company specific (cf. Reiner and Trcka, 2004); i.e. each SC network has a specific design in the sense of network configuration and the planning and control system. In the case of food SC networks, there are additional characteristics that make the design process specific, such as (cf. van der Vorst and Beulens, 2002):

- Shelf life constraints, quality decay of products, and requirements regarded product freshness and food safety;
- Long production throughput times, product dependent cleaning and processing times, production seasonality and (necessity) for quality testing;
- Variability of product quality and supply quantity of farm-based inputs;
- High volume production systems and capital-intensive machinery;
- Specific requirements for logistic processes, such as chilling conditions;
- Weather dependent consumer demands;
- Legislation concerning food production, distribution, trade, quality of products etc.

SC network performance depends to a large extent on external, environmental factors. Roughly, changes in markets, economical, technological, geographical, social and cultural factors, political and legal systems and competition can be classified as external factors. They are characterized by uncertainty and frequently by volatility (Grant et al., 2006). As such, external factors contribute to uncertainty, dynamics and complexity in SC networks. Let us explain this in more detail.

Uncertainty is an inherent characteristic of a SC networks (Van Landeghem and Vanmaele, 2002; Van der Vorst and Beulens, 2002). One of the key sources of uncertainty in the SC is due to the quantity, timing and specification of end-customer demand (Stevenson and Spring, 2007); in food SC network also supply and process uncertainties play a very important role. Uncertainty in a food SC network can be seen as a characteristic of the material, information and financial flow. From logistic viewpoint one can consider different aspects, such as:

- Time: duration or frequency of an activity/process, starting or ending moment of an activity;
- Quantity: supply, demand or physical transformation of the goods;
- Location/place: where do activities take place;
- Quality: of a logistics service or product;
- Cost: fluctuation of currencies, where, when and why additional cost occur.

If not properly managed/considered, uncertainty in SC networks may cause disturbances, sometimes characterized as small deviations, larger disruptions or disasters (Viswanadham and Gaonkar, 2008). The SC network design (with respect to network configuration and planning & control system) influences the sensitivity to the uncertainty, also called *vulnerability*. With the target to stay competitive, firms face the challenge of transforming their operations from a static to a dynamic business environment (Chandra and Grabis, 2007). The *dynamic* character of SC networks is the result of constant change in the business environment.

SCs are *complex* networks (Christopher and Peck, 2004) and in general, SC network complexity is caused by the multiple interactions within the network itself (cf. Asbjørnslett and Rausand, 1999) and by the influence of external factors (cf. Peck, 2005). According to Gribble (2001), as a system grows in complexity, small perturbations can result in large changes in behaviour of the system (also known as the *butterfly effect*). The complexity of a food SC network is influenced by the number of participants, interrelated product and process links, differences in use of technology of the participants, specific standards and legislations concerning food preservation and quality, product characteristics, product assortment, consumer wishes for fresher and more natural products, smaller production lot size, and so on (cf. Tang, 2006; van der Vorst et al., 2009). As a system becomes sufficiently complex, unexpected perturbations and failures inevitably will appear (Grible, 2001). In our context this implies that the complexity of SC networks influences SC network vulnerability.

According to Svensson (2000), *vulnerability* is defined as random disturbances resulting in deviations in the SC of components and materials from normal, expected or planned schedules or activities, all of which may cause negative consequences for the involved manufacturer and its sub-contractors. In our view, the degree of SC network vulnerability depends on:

a) the level of uncertainty, complexity and dynamics,

b) the degree to which the performance requirements are flexible (i.e. customers accept a temporary lower performance), and

c) the degree to which the SC network design is flexible (able to absorb shocks).

The whole provides a base to look for SC network robustness (see Figure 2.1). *A robust food SC network is perceived as being able to continue to function well in the event of disruption in some of its stages* (cf. Dreo et al., 2006).

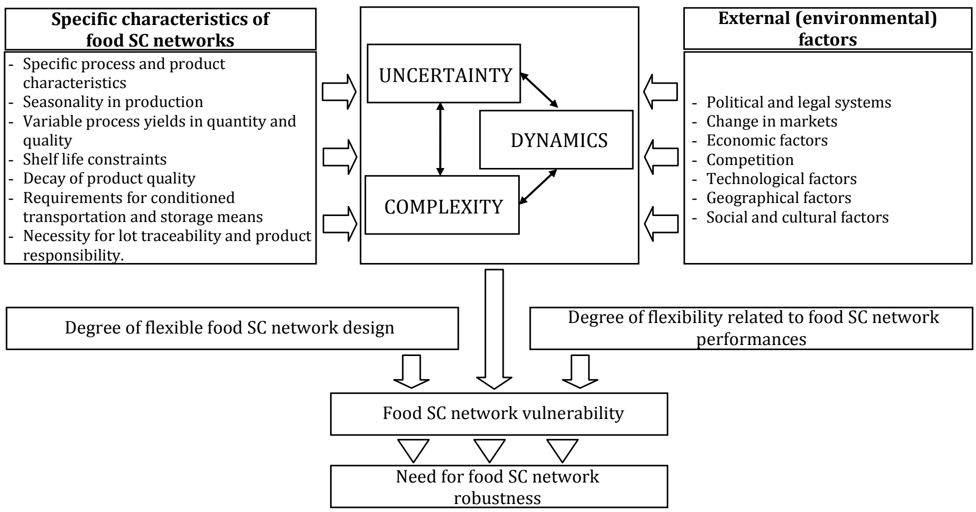

Figure 2. 1. Food SC network vulnerability and robustness.

The concept of flexibility in the SC network is discussed for instance in the works of Garavelli, 2003; Barad and Sapir, 2003; Duclos et al. 2003; Graves and Tomlin, 2003; Gunasekaran et al., 2004; Surie and Wagner 2005; Slack, 2005; Stevenson and Spring, 2007. The concept of robustness in the context of a (food) SC network, does not seem to be uniquely defined. Therefore, we initiated our research on robust SCs with a systematic review of available literature. *Which perceptions of robustness can be found in the literature and how can we relate them to (food) SC networks*?

2.3. Literature research method

Numerous articles contain the terms "robust" and "robustness", e.g. 450.000 papers in *Google Scholar*, December 2007. Moreover, they are used close to concepts of "*stability*" or "*reliability*" and together with "*flexibility*", "*resilience*" and "*adaptability*". Initially, we focused on robustness in SCM literature and collected a few articles that provide the following insights:

- The terms have a specific meaning in different contexts; i.e. as *criterion*, *property* or *measure*;
- Many papers *do not provide a formal definition* nor explanation, but use them in the text only once, mainly as adjective; for example, robust framework, robust understanding, robust process, robust analysis, etc.;
- They are defined at *different levels of abstraction*; highly conceptual definitions and definitions that concretely specify a measurable indicator for a specific problem;
- When used as attribute, they are *mixed with other attributes* such as flexibility and stability;
- Most of the articles that concern robustness are published *recently*.

To perform a systematic search, our research method is done in two phases. The first phase is the choice of the most convenient bibliographic database and criteria for article selection. In the second phase, we performed content analysis of selected articles from the first phase. We selected databases *Scopus*, *Scirus* and *Google Scholar* as the most relevant for our research. Database *Scopus* is used for searching within titles, keywords and abstracts in journals and conference papers. This database is chosen because it contains the largest number of articles with the term "robust". Database *Scirus* and *Google Scholar* are used for searching within text. Research is constrained by several criteria: timeframe of publishing, type of the article and subject areas where papers regarding SC issues are usually published (where it was applicable). For example, in database *Scirus*, we constrained research to:

- Timeframe of publishing - from 1980 to 2007;
- Type of the article – articles published in journals and conference articles;
- Subject areas – Computer Science; Economics, Business and Management; Engineering, Energy and Technology; Mathematics; Social and Behaviour Sciences.

Articles are collected at the beginning of 2007, with constant updates of available articles until December 2007. Although we focused on articles published in journals and conference articles, we included relevant books, monographs, doctoral theses and working papers. Cross-combination of most frequent keywords resulted in 144 papers, and 81 papers concerned SC and robustness issues. Results of our research in the first phase shows that robust(ness) is a popular term, used in many subject areas, as well as in SCM literature.

We identified the main contexts where robustness is used – i.e. design, modelling and strategy, as well as the main attributes that are related to robustness – i.e. flexibility, reliability, resilience, adaptability, stability and vulnerability. We used these terms as keywords in our search. However, flexibility, reliability, resilience, adaptability, stability and vulnerability are also very popular terms and for each of them thousands of publications can be found. Therefore, we limited further research to publications related to SCM.

The term "robust" appears frequently in the context of design, but also a lot of published material can be found in the context of strategy and modelling (Figure 2.2a) in both subject areas; that of SCM as in other subject areas. Moreover, the search shows that robustness is often associated with vulnerability and flexibility, but also with reliability, stability, adaptability and a bit less with resilience (Figure 2.2b). For the purpose of this chapter, we will discuss the most connected terms with robustness: *vulnerability* and *flexibility*.

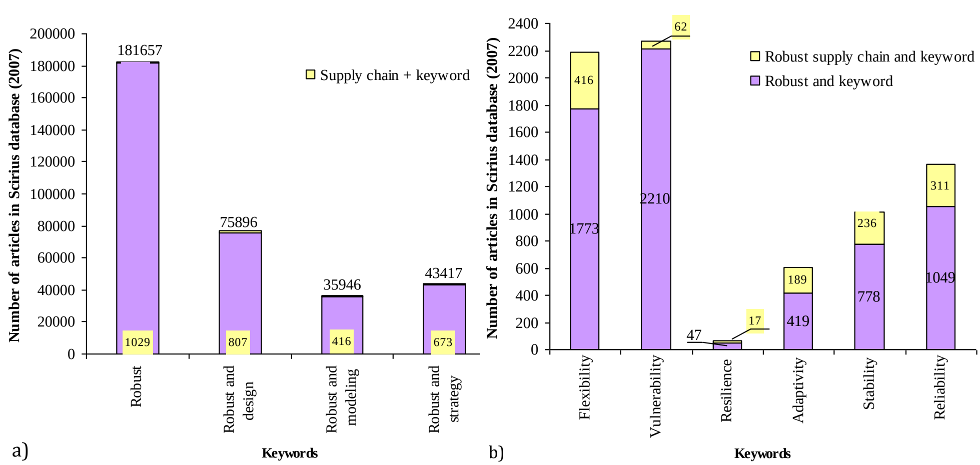

Figure 2. 2. Number of articles that contain keyword "robust" in combination with given keywords (database Scirius, December 2007)

In the second phase, we performed *content analysis* of the collected articles. Main criteria for article selection was a given definition or explanation of what robust/robustness in SC context is. During this searching procedure, we also found new material, relevant for the discussion regarding robustness in general. In total, we selected 60 publications of which 35 publications were related to SCM issues. The chronological analysis of published material shows an increasing interest in subject areas (Figure 2.3a) and in SCM literature (Figure 2.3b).

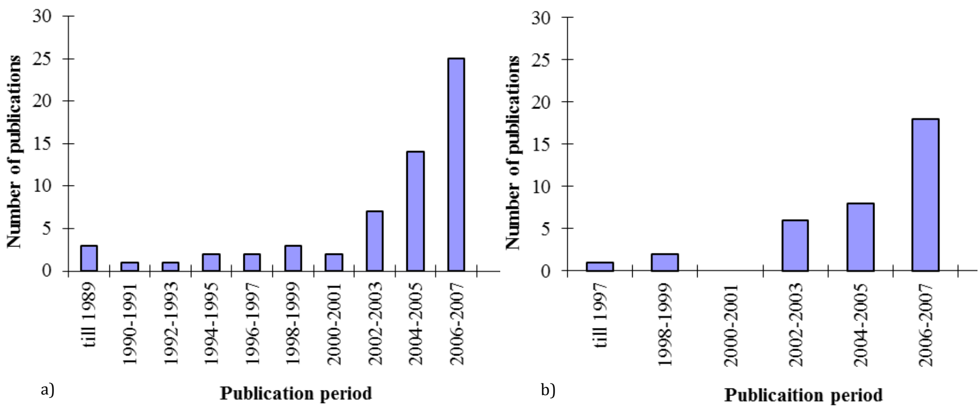

Figure 2. 3. Chronological overview of a robustness issues in a) all reviewed publications and b) reviewed publications in SC context

2.4. Robustness as found in literature

The literature review shows that the term robustness can be defined in many ways, depending on the specific context. We reviewed 60 papers and classified all definitions or explanations regarding robustness in two groups (Figure 2.4): robustness defined at conceptual level and robustness defined at modelling level.

At *conceptual level*, robustness is mainly seen as a property of the system or as a redesign strategy that can be used to improve system performance. This refers to conceptual models that argue, using practical case studies, how the robustness of the system and its performance can be improved. At *modelling level*, robustness is mainly related to concrete properties of quantitative (optimization or simulation) models or solutions in situations where input data are characterized by high variability. As a result, we characterized all papers with respect to the following aspects:

- Is robustness seen as a system property or performance indicator?
- Is robustness used in the context of quantitative models and/or solutions?
- Is robustness used in the context of a design method or (re)design strategy for improving performance?

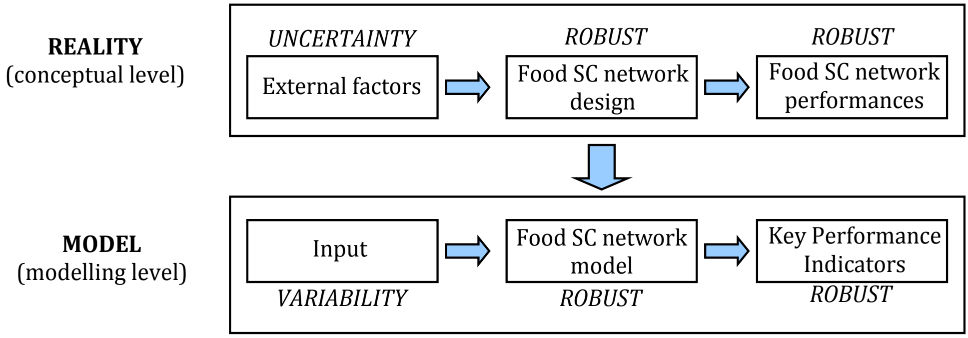

Figure 2. 4. Conceptual and modelling level of (Food) SC network that is considered in robustness definitions

A full characterization is given in Table 2.1. The main definitions are given in two tables in the appendix 2.1: Table A.1 gives the definitions related to SC literature, whereas Table A.2 gives definitions found in the other literature.

Robustness definitions at *conceptual level* are based on the conceptualization of the observable reality regarding the business environment and observed SC network characteristics. In our vision, the business environment can be considered a set of external factors which are characterized by uncertainty. Food SC network characteristics depend on Food SC Network design and result in a certain performance. Therefore, robustness definitions at conceptual level typically include: external factors (A), elements of Food SC Network design (B) and Food SC Network performance (C).

A. The *set of external factors* depends on the system boundary. For a SC network, the set of external factors depends on the type of SC network (global or regional type of SC network) and they contribute to existing uncertainty and complexity. External factors are usually considered in a non-explicit way in robustness definitions, regardless of the robustness approach, e.g. in the definitions of Ferdows (1997) - competitive environment; Tee and Rossetti (2002) - environmental conditions; Reiner and Trcka (2004) - many possible situations; Kleijnen (2005) - many changes in its environment; Mo and Harrison (2005) - sources of uncertainty; Stevenson and Spring (2007) - range of market change. In other definitions of robustness, they are considered more precisely, as a cause of a specific type of disruption, e.g. in the definition of Asbjørnslett and Rausand (1999) as accidental event; in Bundschuh et al. (2003) as failure; in Tang (2006) as normal circumstances and major disruption; in Adhitya et al. (2007) as complete and partial rectifications; in Chandra and Grabis (2007) as external and internal shocks. We conclude:

1. All definitions of robustness consider the influence of external factors (directly or indirectly);
2. External factors contribute to SC network uncertainty and complexity and in that way they can cause a disruption in SC network performance; as a consequence a SC network becomes vulnerable;
3. Robust SC networks should function well enough in normal business circumstances and also in the case of disruption. Disturbances are defined at different impact levels; papers refer to deviations, disruptions and disasters.

B. In order to *design a robust (Food) SC network*, all of the design elements (i.e. the network configuration and planning & control system) have to be taken into account. We found that robustness is mostly related to strategic issues such as SC network structure and configuration (see e.g. Butler, 2003; Mo and Harrison, 2005; Dong, 2006; Stevenson and Spring, 2007) under different forms of uncertainty. There are few papers (e.g. work of Simchi-Levi et al., 2002 and Tang, 2006) in which principles of robust (logistic) strategies are discussed and this issue can be considered as part of a network planning & control system. Based on the reviewed papers we conclude:

1. Only one aspect of SC network design is usually considered, i.e. either the design of robust SC network configurations or the design of robust planning & control strategies;
2. Papers on robust planning and control strategies only discuss very basic principles for improving robustness of SC networks. There is no systematic approach to the robustness issue from a conceptual point of view. Some relevant approaches are considered to design robust SC network, e.g. risk management, the "design for X" technique;
3. One should be aware that a flexible SC network design may absorb several types of disruptions which reduce the need for robustness improvements.

C. The level of competitiveness of a SC network is reflected though the *SC network performance*. Common SC network objectives are related to costs and customer service. The relevance of other objectives depends on the type and characteristics of the SC network. In most of the cases, specific characteristics of SC networks and related objectives are poorly considered. In today's business environment there are increasing requirements toward robust performance, which corresponds to robustness being a desired property of SC networks (e.g. see definitions Asbjørnslett and Rausand, 1999; Bundschuh et al., 2003; Dong, 2006; Adhitya et al., 2007; Chandra and Grabis, 2007). We conclude:

1. At conceptual level, robustness is weakly defined as a performance measure. Only in papers of Mo and Harrison, 2005; Dong, 2006; Dong and Chen, 2007 robustness is defined as a detailed performance measure – although still general, without a relation to a specific industry. In the case of food SC network, the specific characteristics of food industry should be considered (e.g. quality issues, perishability of products etc.);
2. Two approaches can be used to define robust performance. The first approach is based on the idea on robustness as a specific SC network performance indicator next to more traditional indicators. The second approach is based on the idea of robustness as an overall SC network performance indicator (e.g. a "*robustness index*", similar to the work of Dong, 2006).

Many other papers discuss robustness from the *modelling level*; here quantitative models of real systems and its outcomes are presented and the issue of robustness is discussed. Often Operations Research or statistical models are used and robustness is discussed from the aspect of model design and/or quantitative model solution. Here we distinguish three important SC modelling elements: input data (D), SC network model (E) and model solution or Key Performance Indicators (KPIs) (F).

D. Many robustness definitions in SCM literature are based on the work of Box and Jenkins from 1976 and they are related to the quality of *input data*, data uncertainty (e.g. Goetschalckx et al., 2002; Snyder, 2003) and analysis of model robustness (e.g. Tee and Rossetti, 2002; Wu, 2006). Though all model assumptions are usually well defined, we found that only few types of data are considered i.e. most often data regarding customer demands, supply quantities and lead times.

E. Robustness from the aspect of SC network modelling is related to model design and modelling method. Incorporation of robustness into model design is mainly present in the application of the Taguchi method for developing stochastic models (e.g. Mo and Harrison, 2005) or simulation models (e.g. Gaury and Kleijnen, 1998). In other methods (such as robust optimization, stochastic programming), robustness is based on the robustness concept developed by Gupta and Rosenhead (1968), i.e. examination of the optimal solution of a particular problem and selection of robust solution based on certain criteria (e.g. work of Snyder, 2003; Bundschuh et al., 2006; Wu, 2006). We conclude that there is a lack of an integral approach to robust model design.

Table 2. 1. Papers with definitions of robustness.
Work that covers robustness in SC network context in italics

Authors	Context			Robustness defined		Year
	Property or performance	Solution and/ or model	Design method or strategy	Conceptual level	Application or model	
Gupta and Rosenhead (1968)		X		X	X	1968
Rosenhead et al. (1972)		X		X	X	1972
Pye (1978)		X		X		1978
Lasserre and Merce (1990)	X	X			X	1990
Schruben et al., (1992)			X		X	1992
Ulusoy and Uzsoy (1994)		X	X		X	1994
Mulvey et al. (1995)		X			X	1995
Ferdows (1997)	*X*			*X*		*1997*
McCaskey and Tsui (1997)			X		X	1997
Gaury and Kleijnen (1998)			X		X	1998
Zapfel (1998)		*X*			*X*	*1998*
Asbjørnslett and Rausand (1999)	*X*			*X*		*1999*
Gribble (2001)	X		X	X		2001
Jensen (2001)	X			X		2001
Carlson and Doyle (2002)	X			X		2002
Simchi-Levi et al. (2002)			*X*	*X*		*2002*
Tee and Rossetti (2002)		*X*			*X*	*2002*
Van Landeghem and Vanmaele, (2002)		*X*	*X*	*X*	*X*	*2002*
Butler (2003)		*X*			*X*	*2003*
List et al. (2003)		*X*			*X*	*2003*
Snyder (2003)	*X*	*X*		*X*	*X*	*2003*
Anderies et al. (2004)	X			X		2004
de Neufville (2004)	X		X	X		2004
Goetschalckx et al (2004)		*X*			*X*	*2004*
Herroelen and Leus (2004)		X			X	2004
Kutanoglu and Wu (2004)		X			X	2004
Reiner and Trcka (2004)	*X*	*X*		*X*		*2004*
Santoso et al. (2004)		*X*			*X*	*2004*
Arndt and Müller-Christ (2005)	X			X		2005
Esterman and Ishii (2005)	*X*		*X*	*X*		*2005*
Goetschalckx and Fleischmann (2005)		*X*			*X*	*2005*
Jen (2005)	X			X		2005
Kleijnen (2005)			*X*	*X*		*2005*
Mo and Harrison, (2005)		*X*	*X*	*X*	*X*	*2005*
Santoso et al. (2005)		*X*		*X*		*2005*
Gallopin (2006)	X			X		2006
Gaonkar and Viswanadham (2006)		*X*	*X*	*X*	*X*	*2006*
Ismail and Sharifi (2006)	*X*			*X*		*2006*
Lempert et al. (2006)			*X*		*X*	2006

Table 2.1. Papers with definitions of robustness (continued)
Work that covers robustness in SC network context in italics

Authors	Context			Robustness defined		Year
	Property or performance	Solution and/ or model	Design method or strategy	Conceptual level	Application or model	
Bundschuh et al. (2006)	*X*	*X*			*X*	*2006*
Dong (2006)		*X*			*X*	*2006*
Dreo et al (2006)	X			X		2006
Snyder et al. (2006)		*X*		*X*		*2006*
Tang (2006)			*X*	*X*		*2006*
Tang (2006a)			*X*	*X*		*2006*
Wagner and Bode (2006)	*X*			*X*		*2006*
Wijnands and Ondersteijn (2006)	*X*			*X*		*2006*
Wu (2006)		*X*			*X*	*2006*
Adhitya et al., (2007)	*X*			*X*		*2007*
Chandra and Grabis (2007)	*X*			*X*		*2007*
Deblaere et al. (2007)		X			X	2007
Dong and Chen (2007)		*X*			*X*	*2007*
Genin et al., (2007)		X	X		X	2007
Groves and Lempert (2007)			X		X	2007
Leung et al. (2007)		*X*			*X*	*2007*
Leung et al. (2007a)		*X*			*X*	*2007*
Meepetchdee and Shah (2007)		*X*				*2007*
Mudchanatongsuk et al., (2007)		*X*			*X*	*2007*
Nagurney and Qiang (2007)		X			X	2007
Ouyang (2007)		*X*			*X*	*2007*

F. Robustness from the aspect of model solution or key performance indicators (KPIs) is mainly considered through analysis of *solution robustness* (e.g. work of Snyder, 2003; Wu, 2006) and calculation of a robustness index (e.g. Dong, 2006). An extensive review of robust models and measures can be found in the doctoral thesis of Butler (2003). A lot of work considers the examination of solution robustness without direct connection and impact on SC network design and performances. In most papers, analysis of solution robustness is based on a cost objective function. However, for SC networks, more than one important performances are identified such as cost, customer service and – in food SCs - product quality (van der Vorst et al., 2009). This gives a challenge to construct a robustness index that captures all relevant KPIs.

2.5. Conclusions and further research

Due to the influence of external (natural) uncertain factors on Food SC network, increasing complexity and dynamics, food SC networks become more vulnerable. This makes the concept of robustness an interesting topic. We started our investigation on this topic by performing a literature research on this concept in as well SCM literature, as surrounding literature that best could be characterized as Operations Research and Engineering. About 60 papers were investigated on content. First of all, a distinction was made on whether robustness was defined on conceptual level, or whether the robustness concept has been quantitatively modelled. Furthermore, we characterized papers as describing robustness as property or performance measure, whether a model or solution was present and whether the paper provides a design method or strategy.

Due to the influence of external factors on SC uncertainty, complexity and dynamics, companies become more vulnerable, such that robustness becomes an important issue. Based on the previous discussion, reflection and concluding remarks, we highlight a number of *research opportunities*:

1. Robustness is an important factor for achieving SC network competitiveness. Therefore, SC network robustness could be more *precisely defined* and related to certain business/key *performance indicators* (not only to financial ones) to guide SC network improvement programs.
2. All relevant *external factors* should be identified in the case of a specific SC network and their influence to vulnerability should be investigated for specific cases.
3. In order to work with SC network robustness, it is useful to come to *degrees of* SC network *vulnerability*. As, SC network vulnerability is caused by some type of disruptions, a more precise *categorization of disruptions* in their relation with strategic, tactical and operational level of decision making would be useful.
4. There is a need for a *systematic overview of (re)design strategies* that may improve SC network robustness (and considers all elements of SC network design) and a list of appropriate criteria to support the selection of the right strategy in a specific case.
5. When modeling and assessing the robustness of food SC network the *specific characteristics of these networks* should be incorporated in the model.
6. Using a *robustness index* can be useful in quantitative modeling and it can be a powerful tool for measuring SC network robustness. At the moment such a tool is lacking in literature.

Appendix 2.1

Table A. 1 Definitions of robustness in SC literature

Definitions of robust/robustness:	*Authors*
Robustness seen as a system property or performance indicator	
A robust network is one that can cope with changes in the competitive environment without resorting to extreme measures.	Ferdows (1997)
System's ability to resist an accidental event and return to do its intended mission and retain the same stable situation as it had before the accidental event.	Asbjørnslett and Rausand (1999)
At strategic level robust plan should stay valid in many possible situations. (SC context)	Reiner and Trcka (2004)
Ability of the SC to maintain a given level of output after a failure	Bundschuh et al. (2003)
The SC is able to withstand external and internal shocks, such as loss of suppliers, labor disputes, and natural disasters, because suppliers can be replaced, manufacturing can be switched to alternative facilities, and transportation routes can be rearranged.	Chandra and Grabis (2007)
A robust system should be capable of handling both complete and partial rectifications (in the context of petrol SC)	Adhitya et al., (2007)
Robustness used in the context of quantitative models and/or solutions	
Robust configuration is "a configuration whose objective function value deviates little from the optimal objective function value when the cost parameters change."	Goetschalckx, et al. (2001), in Butler (2003)
A robust model should still be able to provide accurate performance prediction/approximation for the inventory system even when the actual environmental conditions have violated the modeling assumptions.	Tee and Rossetti (2002)
Robustness of SC network is the extent to which the network is able to carry out its functions despite some damage done to it, such as the removal of some of the nodes and/or links in a network.	Dong (2006) Dong and Chen (2007)
Robust SC will avoid the bullwhip effect and all its deleterious economic consequences no matter what the customer does.	Ouyang (2007)
Robustness used in the context of a design method or design strategy for improving performance	
A robust SC design finds a SC configuration (or perhaps a group of SC configurations) that provides robust and attractive performance while considering many sources of uncertainty.	Mo and Harrison (2005)
A robust SC keeps its design fixed, and can still accommodate many changes in its environment.	Kleijnen (2005)
In order to motivate firms to secure their SCs, "robust" strategies need to be developed that serve dual purposes. 1. These strategies should be able to help a firm to reduce cost and/or improve customer satisfaction under normal circumstances. 2. The same strategies should enable a firm to sustain its operations during and after a major disruption.	Tang (2006) Tang (2006a)

Legend: SC- supply chain

Table A. 2 Definitions of robustness in other literature

Definition of robust/robustness as:	*Authors*
Robustness seen as a system property or performance indicator	
Robustness is defined as "ability of a system to continue to operate correctly across a wide range of operational conditions and to fail gracefully outside of that range".	Gribble (2001)
Robustness is defined as "ability of a system to maintain its operational capabilities under different circumstances".	de Neufville (2004)
A robust organization is able to deal with uncertainties related to autonomous control of logistics processes without compromising the basis of its future operations – i.e. specific functions the organization strives to achieve and on that way to maintain certain identity.	Arndt and Müller-Christ (2005)
A robust schedule is a quality schedule expected to still be acceptable if something unforeseen happens, while a flexible schedule is a quality schedule expected to be easy to change.	Jensen (2001)
Aggregate plan is said to be robust if there exists a feasible dynamic disaggregation policy which means that policy depends on the information available at that period.	Lasserre and Merce (1990)
By robustness, we mean the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment.	Carlson and Doyle (2002)
Robustness is a measure of the effectiveness of a system's ability to switch among multiple strategic options. Robustness in this sense reflects the system's ability to perform multiple functionalities as needed without change in structure.	Jen (2005)
Robust systems are desired because of their ability to continue to function in the event of breakdown of one of their components.	Dreo et a. (2006)
Robustness used in the context of a design method or design strategy for improving performance	
Method for improving product or manufacturing process design by making the output response insensitive (robust) to difficult-to-control variations (noise).	McCaskey and Tsui (1997)
Robust (product) design consists of searching for a product design that guarantees low variations in the performance level when the environment changes.	Gaury and Kleijnen (1998)
A set of design methods for improving the consistency of a systems function across a wide range of conditions.	De Neufville (2004)

3. A framework for designing robust food supply chains

This chapter is based on the published journal article:

Vlajic, J.V., van der Vorst, J.G.A.J., and Haijema, R., (2012)

"*A framework for designing robust food supply chains*",

International Journal of Production Economics,
Vol. 137, Is. 1, pp. 176-189.

In this chapter we answer Research Question **2**:

What are the main elements that have to be considered in the design of robust SCs and what are the relationships between these elements?

Abstract

After years of emphasis on leanness and responsiveness businesses are now experiencing their vulnerability to supply chain disturbances. Although more literature is appearing on this subject, there is a need for an integrated framework to support the analysis and design of robust food supply chains. In this chapter we present such a framework. We define the concept of robustness and classify supply chain disturbances, sources of food supply chain vulnerability, and adequate redesign principles and strategies to achieve robust supply chain performances. To test and illustrate its applicability, the research framework is applied to a meat supply chain.

Keywords: Disturbances; Vulnerability sources; Preventive redesign strategies; Reductive redesign strategies; Supply chain performances; Supply chain vulnerability

3.1 Introduction

Today's business environment has become an international playing field in which companies have to excel in logistics performance, i.e. markets require full responsiveness, high quality products and high reliability of supply in small time windows at the lowest cost. As a consequence, supply chains (SCs) have eliminated most non-value adding activities and have become leaner. However, lean SCs without much inventory are more vulnerable to disturbances in logistic processes, which mean that they might be less consistent in their performance, i.e. are less *robust* (cf. Kleindorfer and Saad, 2005; Dong, 2006). Consequently, the competitive power of vulnerable SCs in the market may diminish. In practice, in recent years there have been reported many events that have led to disturbances in SCs processes (e.g. supplier failures caused by natural disasters or fires in the warehouses, delivery delays due to traffic accidents, product recalls due to lack of fulfilment of quality or safety requirements, etc.). Because of that, there is increasing interest by practitioners and academics to reduce SC vulnerability and design robust SCs. This holds especially for food SCs as these chains have specific characteristics that increase its vulnerability, such as seasonality in supply and demand and a limited shelf-life of products.

In supply chain management (SCM) theory, robustness and vulnerability are perceived as opposite though not mature concepts (Asbjørnslett and Rausand, 1999; Wagner and Bode, 2006). As a term, *robustness* has a broad meaning and it is often couched in different settings (Qiang et al, 2009). However, despite its frequent use, there is no general, widely accepted definition (Arndt and Müller-Christ, 2005; Vlajic et al., 2010).

In a SC literature robustness is mainly considered as the ability of the system to continue to function well in the event of a disruption (Dong, 2006; Tang, 2006; Waters, 2007) i.e. an unexpected event that severely impacts performance. Here, three points get attention. First, if the system functions well depends on what is measured and how it is measured and it varies from application to application (Snyder, 2003). Second, robustness of the SC could be jeopardized by various kinds of unexpected events: accidental events (e.g. a fire in the facility, a machine failure, flood, or a traffic accident), and events that result from or belong to the systems characteristics (e.g. poor communication or decision making processes). Third, consequences of unexpected events could be measured at process or at system's (company or SC) level and the severity depends on system's design. The severity of the consequences determines the level of SC robustness, or its opposite SC vulnerability. In this chapter we focus on (process) disturbances, i.e. any consequences of unexpected events at the process level and their impact to the robustness of the SC performance.

A literature review on SC robustness (Vlajic et al, 2010) shows that there is a lack of an integral framework that guides companies in managing disturbances and designing robust SCs. With this chapter, we aim to contribute to SCM theory by developing such an integrated framework for the design of robust (food) SCs. To develop this framework we have conducted an extended literature review, participated in a number of workshops and conducted several interviews with field experts to get insight into practical issues in food industry relevant for the framework. To test it, we applied it to a case in the meat SC, as one of the main chains in food industry. The data collection is based on observations, historical data and semi-structured interviews.

This chapter is organized as follows. Section 2 discusses what SC robustness is. Section 3 presents the framework for designing robust food SCs, and here we focus on the following elements: SC disturbances, sources of vulnerability and redesign strategies. Section 4 presents the application of the research framework in the case study. We conclude the chapter with a discussion and issues for further research.

3.2 What is SC robustness?

The term robustness can be defined in many ways, depending on the specific context and research area (see Jen, 2005; Bundschuh at al., 2003; Qiang et al, 2009). In the SCM literature, robustness is considered both at a qualitative conceptual level and at a quantitative modelling level (Vlajic et al, 2010).

At *qualitative conceptual level*, robustness is considered as an important property of SCs or as a strategy that can be used to improve SC resilience. In both cases, robustness is related mainly to SC vulnerability and uncertainty in general, and vulnerability is seen as consequence of various disruptions (Tang, 2006). One of the first papers that considered robustness, resilience and vulnerability is the paper of Asbjørnslett and Rausand (1999). They introduced robustness and resilience as concepts that are opposite of the vulnerability concept. They define different kinds of disruptions that affect the business performances of a production system. Asbjørnslett (2009) continued this work in the context of SCs. According to him, a *robust* system (SC) has the ability to resist disruptions, retaining its system structure intact, whilst a *resilient* system is adaptable, i.e. it will adapt to regain a new stable position. This approach to robustness is used also by Ferdows (1997) in the context of network robustness. Considering uncertainty in the global business environment, Ferdows (1997) made a relation between robustness and security and introduced the term "robust network" (Table 3.1). In this definition, extreme measures imply a change in SC structure. Following the same line of thoughts, some authors associated SC robustness with its ability to keep its structure fixed (intact) in all situations including disruptions (e.g. see work of Bundschuh et al. 2003; Kleijnen, 2005; Dong, 2006; Chandra and Grabis, 2007; Dong and Chen, 2007; Viswanadham and Gaonkar, 2008). In these papers, the definitions of robustness imply that SCs are robust if their structure is not changed and that SC robustness could be jeopardized only by disruptions. Moreover, dependent on the specific SC design various kinds of unexpected events could jeopardize the SC robustness, i.e. make SC vulnerable. Examples of various definitions on SC robustness are presented in Table 3.1.

Table 3. 1. Some definitions of robustness in the SC context

Definitions of robustness:	*Authors*
The ability of a network to cope with changes in the competitive environment without resorting to changes in the network structure.	Ferdows (1997)
The system's ability to resist an accidental event and return to do its intended mission and retain the same stable situation as it had before the accidental event.	Asbjørnslett and Rausand (1999)
The ability of a SC design to find a SC configuration that provides robust and attractive performance while considering many sources of uncertainty.	Mo and Harrison (2005)
The ability of SC to maintain a given level of output after a failure	Bundschuh et al. (2003)
The SCs ability to withstand external and internal shocks	Chandra and Grabis (2007)
The ability of a SC network to carry out its functions despite some damage done to it, such as the removal of some of the nodes and/or links in a network.	Dong (2006) Dong and Chen (2007)

At *quantitative modelling level*, robustness is mainly used in a context of modelling solutions or models for various problems in SCs – such as planning (e.g. Zapfel, 1998; Van Landeghem and Vanmaele, 2002; Goetschalckx and Fleischmann, 2005; Leung et al., 2007), scheduling (e.g. Kutanoglu and Wu, 2004; Adhitya et al., 2007), network design (e.g. Snyder, 2003; Bundschuh et al., 2003; Mo and Harrison, 2005; Meepetchdee and Shah, 2007), inventory management (e.g. Tee and Rossetti, 2002; Ouyang, 2007) etc. Today, the term robustness as a measure is used a lot in Operations Research literature – especially in stochastic programming (e.g. see work of Goetschalckx and Fleischmann, 2005; Mo and Harrison, 2005) and robust optimisation (e.g. see work of Mulvey et al, 1995; Snyder, 2003; Wu, 2006; Leung et al., 2007). The precise formulation of robustness depends on the particular technique used or type of the problem that is modelled. For instance, in robust optimization the modelling solution is defined as robust if it performs well for all scenarios of input data (Snyder, 2003), and a model is defined as robust if it remains "almost feasible" for all data scenarios (Mulvey et al, 1995). The definition of "performing well" varies from application to application and choosing an appropriate measure of robustness is part of the modelling process (Snyder, 2003). Despite an abundance of literature in the context of model and solution robustness, little work has focused on measuring SC's robustness, i.e. the ability of a SC to cope with unexpected events (Dong and Chen, 2007; Qiang et al., 2009).

Definition of robustness

In our view, SC robustness is a *desired property of a SC that is reflected in SC performances*. That is extremely important because today's business environment is characterized by increasing requirements toward robust performances (e.g. demands for reliable supply and higher product quality levels within smaller delivery time windows). According to Waters (2007, p.159), a traditional way in business specifies an acceptable range for specifications, and the performance is considered acceptable if it stays within this range. We define *SC robustness* as

the degree to which a SC shows an acceptable performance in (each of) its Key Performance Indicators (KPIs) during and after an unexpected event that caused disturbances in one or more logistics processes.

To operationalize this definition, a SC is robust with respect to a KPI if the value of that KPI, adequately measured over an observation period, is sustained in a predefined desired range, even in the presence of disturbances. We call this predefined desired range the *Robustness Range*, and it is characterized by a lower and/or upper level. If a KPI performs above or below the robustness range, the SC is considered vulnerable. The stronger and longer the negative impact to performances is, the more vulnerable SC is to that disturbance.

3.3 Research framework

Now that we have defined SC robustness, this section discusses our research framework for designing robust (food) SCs. We start with a definition of the SC and SC scenario as the study of the scenario in a specific case may identify elements that could cause SC vulnerability as well as elements that could mitigate it.

The literature provides many definitions of SCs, but in general it can be said that a SC is a group of actors that perform specific roles and processes linked to each other via goods, information and money flows, using specific infrastructures aiming to fulfil consumer wishes at lowest cost (van der Vorst, 2000). Based on this definition we use the term SC scenario to describe the SC instance at hand. A *SC scenario* is an internally consistent view of a possible instance of the logistics SC concept, i.e. the managed, managing, and information systems and organization structure (van der Vorst, 2000). It considers relevant *contextual factors* (i.e. specific characteristics of food SCs such as product quality requirements, as well as requirements that come from specific product–market combinations). The *managed* system refers to the physical design of the network and a facility and all other elements that perform logistic activities (such as equipment, vehicles, and people), as well as product characteristics. The *managing* system refers to planning, control and co-ordination of logistic processes in the SC while aiming at realizing strategic SC objectives and logistical objectives within the restrictions set by the SC configuration. The *information* system refers to information and decision support systems within each of the decision layers of the managing system (from annual to daily planning), as well as the IT infrastructure needed. The *organization* structure refers to tasks, authorities and responsibilities of the departments and executives within the organization and SC as well as the coordination of tasks in order to realize defined objectives.

The main objective of the framework is that it helps in determining the best SC scenario that will enable robust SC performances for given circumstances. When we overview and integrate the literature on SC robustness and combine it with the findings of workshops and interviews (presented in Wognum et al. 2009), we find the following common steps that are relevant in this (re)design process:

1. The description and analysis of the SC scenario for a particular case and the identification of KPIs;
2. The identification of unexpected events and disturbances that affect performances;
3. The assessment of performances, i.e. how much and how long can the SC withstand disturbances?
4. The identification of sources of vulnerability that explain process disturbances, and as such which may (strongly) affect the robustness of performance and eventually increase the vulnerability of the SC.
5. The identification of appropriate redesign strategies that eliminate disturbance by acting on sources of vulnerability or that reduce the impact of the disturbance by disabling the domino effect to other processes and SC performances.

Let us give an example to clarify. Several hours delay of a delivery (i.e. a disturbance in the transport process) is caused by a traffic accident on the road (unexpected event), and this traffic accident could happen due to a poor traffic signalization, bad infrastructure or an inexperienced driver (which are vulnerability sources). Consequences of delays can be measured in potential inventory shortages and due to a domino effect as well in underachievement of production output, inventory shortage of final products or low delivery reliability to customers. In this case, the delivery performance is not robust as well and the entire SC can be signalled "vulnerable". Appropriate redesign strategies should be selected and applied to improve this vulnerability.

Figure 3.1 presents the research framework in which all elements are brought together.

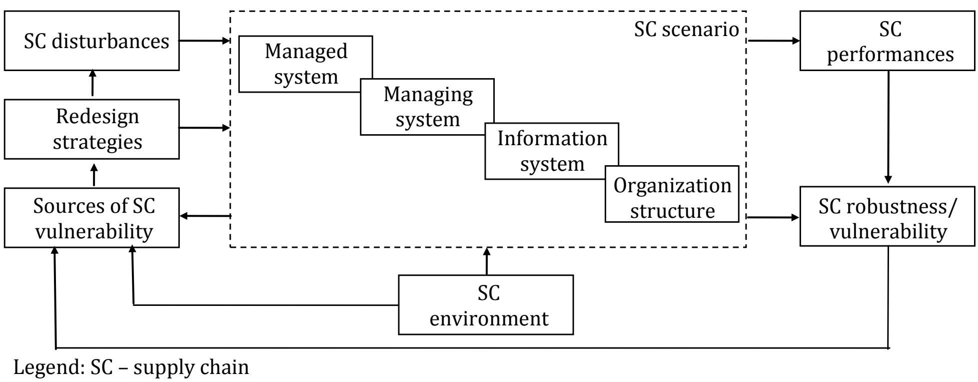

Figure 3. 1. Research framework for designing robust (food) SCs

According to Viswanadham and Gaonkar (2008), an increased awareness of the existence of SC disturbances and their causes may enable better preparedness for handling or preventing them. In other words, the sources of vulnerability and related disturbances are the base for determining appropriate redesign strategies, i.e. strategic as well as tactical plans and operational actions that should increase the robustness level. The implementation of an appropriate redesign strategy implies a change in one or more elements of the SC scenario. As a result either the vulnerability source is eliminated (and therefore the frequency of disturbance is reduced) or the system becomes less vulnerable as the domino effect is disabled (and therefore the impact of disturbances in the SC is reduced). For example, the impact of a disturbances in the delivery of raw materials is reduced either by having buffer stocks or one eliminates or reduces the occurrence of such an disturbance by sourcing from multiple suppliers and having timely information that could trigger emergency actions. Alternatively the impact of a raw material delivery disturbance to a shortage of final products can be reduced by keeping a higher inventory level of final products.

The following sections will classify respectively disturbances, sources of SC vulnerability and SC redesign strategies.

3.3.1 SC disturbances

In the SCM literature, there are only a few papers that focus on a definition and characterization of disturbances. Svensson (2000) introduced a conceptual definition of disturbance. He defined disturbance as "a deviation that causes negative consequences for the firm involved in the SC". Melnyk et al. (2009) on the other hand defined SC disturbance from an operational viewpoint as the output of a chain of events triggered by an unexpected event at one point in the SC that adversely affect the performance of one or more components located elsewhere in the SC". In line with Melnyk et al. (2009) we define *SC disturbance as*

a minor or major deviation, or failure of one or more logistics processes triggered by unexpected events in the SC or its environment resulting in poor performance of the process itself, company and potentially along the SC in a given time period.

In line with work of Scipioni et al, (2002), disturbances can be characterised by a number of elements, i.e. the *frequency of occurrence, the possibility of detection and the impact on SC performance.* In our work, we also consider disturbance *cause* and *size*. According to Svensson (2000) *causes* of disturbances are related to volume and quality. Causes of disturbances in volumes are related to a lack of materials for downstream activities in the chain, and we refer to it as the *quantitative dimension* of disturbances as it considers unexpected changes in quantity of materials. Causes of disturbances in product quality are related to deficiencies in materials in the SC, and we refer to it as the *qualitative dimension* of disturbances as it considers unexpected changes in quality of materials. We extend the disturbance classification of Svensson (2000) by adding the *time dimension* of disturbances that is related to unexpected changes in beginning or ending of process realization, or process duration (i.e. delays or idle times).

In line with the thoughts of van der Vorst and Beulens (2002), we express the *size* of the disturbance in the loss of value of relevant KPIs of the related logistics process that is directly affected by the unexpected event. A minor deviation of a KPI from the norm represents a small disturbance. At the process level it usually represents an acceptable variation in the process outcome and it is considered as part of "business as usual". A major deviation of a KPI from the norm represents a large disturbance, i.e. the process is only partially realized. Extreme values of process KPIs represent a failure of the process execution. Note that the choice of relevant KPIs, their norms and deviation level is case dependent (determined by the SC scenario). An example of various sizes of disturbances and dimensions for one KPI is presented in Table 3.2.

The possibilities for disturbances *detection* affect also the selection of redesign strategies. Disturbance detection depends on the characteristics of the process, as well as on the decision of the management to monitor and trace disturbances in the SC. For that purpose, various techniques could be used, such as Data mining and Statistical Process Control (Shukla and Naim, 2007). The number of disturbances in an observation period represents its *frequency*.

Table 3. 2. Example of classification of disturbances in delivery process

Dimension		*Quantity dimension*	*Quality dimension*	*Time dimension*
Size	KPI	Loss of material during transport	Number of products damaged in transport	Transport time
Minor deviation		A few products are lost	A few product are damaged	A small delay
Major deviation		A shipment is partially received	A significant part of the shipment is damaged	A significant delay
Failure		Loss of an entire shipment	All products of a shipment are damaged	Inability to perform delivery in required time window

In the end, the *impact* of disturbances on robustness of SC performances is crucial. In principle, the impact of a disturbance depends on the flexibility and responsiveness of the SC to adapt to the new situation caused by an unexpected event. Therefore, the impact of a disturbance can be local (e.g. delivery failure can have local impact on transport performance, but it will not jeopardize the production process if there is enough inventory or if a backup delivery option exists) or system wide (e.g. harvest failure or animal diseases outbreak can cause lack of raw material which effects will be transmitted through the whole chain). In both cases, the causality of events has to be considered because a disturbance in one process can cause a domino effect and affect other processes (Waters, 2007) and cause amplification of the impact (Wu et al., 2007). The Bullwhip effect can be also seen as a system wide impact of disturbances in demand along the chain (Wagner and Bode, 2006).

3.3.2 Sources of SC vulnerability

In line with Juttner et al. (2003), we define risk sources as environmental, organizational or SC-related variables that cannot be predicted with certainty and that have impact on the SC performance. In a similar manner, we define *vulnerability sources as*

> *characteristics of the SC or its environment that lead to the occurrence of unexpected events and as such, they are direct or indirect causes of disturbances.*

In literature, there are several approaches to classify vulnerability sources. Based on the reviewed literature (e.g. Albino and Garavelli, 1995; Mason-Jones and Towill, 1998; Asbjørnslett and Rausand, 1999; Svensson, 2000; Scipioni et al, 2002; Van der Vorst and Beulens, 2002; Waters, 2007; Simchi-Levi et al., 2008; Asbjørnslett, 2009) we distinguish two basic groups of vulnerability sources: internal and external sources. Within these two groups, we found a number of generic sources that could be found in almost any SC, as well as specific sources for food SCs. These specific sources result from the specific characteristics of food chains, such as the perishability of goods, the importance of food safety and quality management, the valorisation of by-products, the variability in process yield, and the rigid time constraints (Van der Vorst, 2000).

The roots of *external sources* of SC vulnerability are in the SC environment; some of them are controllable to some extent (e.g. societal or financial sources), others are not (some market sources as well most of environmental sources), see Simchi-Levi et al. (2008, p. 316). We have extracted a list of external sources from the reviewed literature, and classified them to 21 main sources using the classification criteria of Asbjørnslett and Rausand (1999) and Wu et al. (2006) and assigned them codes (see Figure 3.2, e.g. MX – <u>M</u>arket source, E<u>x</u>ternal factor).

Roots of *internal sources of SC vulnerability* are within the SC, i.e. within the elements of the SC scenario (the managing, managed, and information systems or in the organizational structure). From a company perspective, these internal sources are controllable to some extent (Simchi-Levi et al., 2008, p. 316), depending on their origin: within the company or within the SC. Sources of vulnerability at the company level are mostly controllable (Wu et al, 2006) and can be resolved when they result directly from choices and actions of the company's management (Ritchie and Brindley, 2009). Internal sources related to product characteristics, such as the quality decay of fresh food can be controlled only partly. The sources of vulnerability at the SC level are partially to fully controllable (Wu et al, 2006). They come from the supply and demand side of the focal company and the controllability level depends on the level of

SC integration and collaboration. According to Qiang et al. (2009), till now research has been mainly focused to vulnerability sources that come from the demand-side of the focal company, such as fluctuations in the demand for products, as opposed to the supply-side sources, which are related to uncertain conditions that affect the production and transportation processes of the SC. From the literature we have extracted a list of internal vulnerability sources, classified them in 41 main sources according to the controllability level and the elements of the SC scenario and we have assigned codes: e.g. G – managinG system, C – Company level (Figure 3.2).

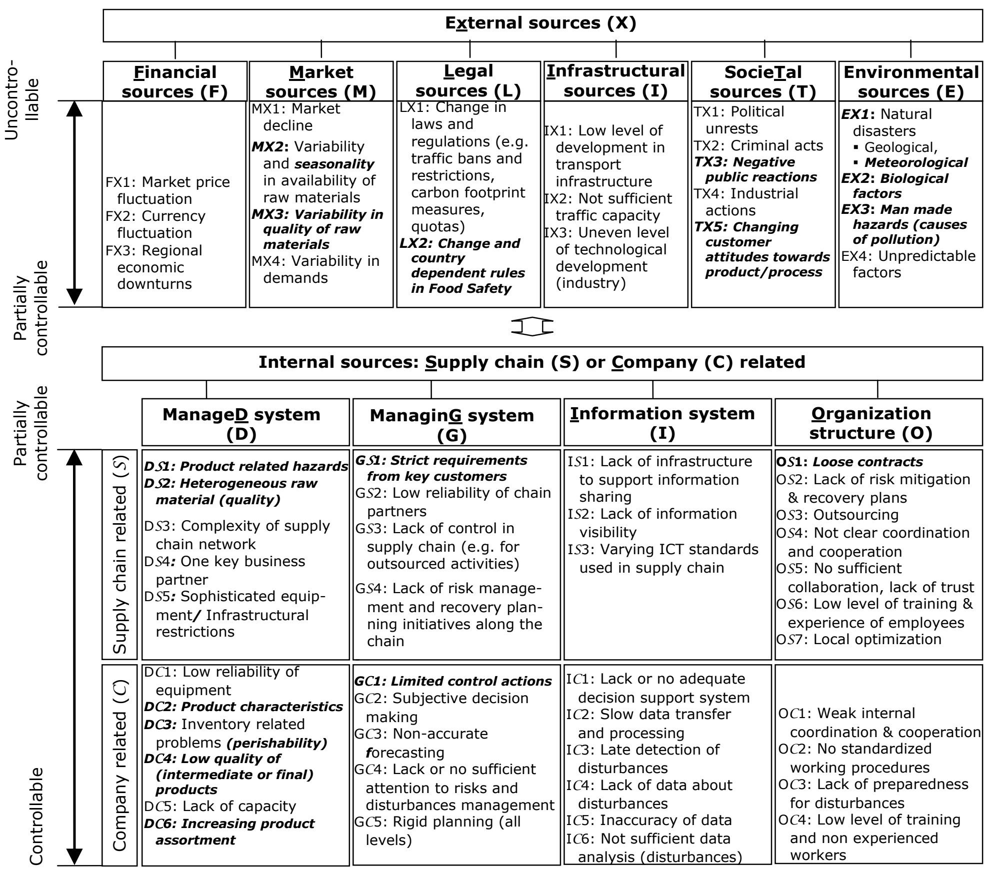

Figure 3. 2. List of sources of SC vulnerability (***bold-italic*** letters denote specific sources related to food SCs) and controllability level (from company's management perspective)

Each of these main sources can have multiple forms (e.g. low quality of raw material can manifest as damaged or spoiled products, or as products with a bad organoleptic characteristics, etc.).

Additionally, it has to be taken into account that sources of vulnerability are interconnected with each other, both within each level and across the levels (Asbjørnslett and Rausand, 1999; Peck, 2005). In that way, they make a chain of causes and consequences, which effects are observable as disturbances in the realization of logistics processes.

In this chapter we focus mainly on internal sources of vulnerability (company and SC level sources).

3.3.3 Categorization of redesign strategies

In SCM literature many redesign principles are given (also referred as risk responses, risk protection strategies, mitigation strategies, and mitigation tactics), and in essence all of them represent possible approaches to define the most appropriate way of dealing with risks and disturbances in the SC. The principles are either related to the concept of uncertainty (Van der Vorst, 2000; Lee, 2002; Simchi-Levi et al., 2002; van der Vorst and Beulens, 2002; Simangunsong et al., 2008), and more recently, to disturbance and risk (e.g. Zsidisin et al., 2000; Tang, 2006, 2006a; Tomlin, 2006; Waters, 2007; Hopp, 2008; Macdonald, 2008; Shimchi-Levi et al., 2008; Dani, 2009). Van der Vorst and Beulens (2002) present an overview of SC redesign principles to deal with uncertainties, such as changing the roles and processes in the SC, reducing customer order lead times, coordinating logistical decisions and creating information transparency. Simchi-Levi at al. (2008) offer several approached to deal with risks, depend on their controllability. Peck (2005) mentions strategies such as outsourcing and contract forms that should be used to mitigate SC risks and to achieve SC resilience. Tang (2006) identifies nine strategies that can be implemented under normal business circumstances or after major disruptions, and he describes main challenges for selecting an appropriate (redesign) strategy. In another paper (Tang, 2006a), those strategies are typified according to four SCM areas: supply management, demand management, product management and information management. Based on our review, we define *redesign strategies as*

sets of strategic and tactical plans and operational actions that aim to reduce the vulnerability of SCs based on one or more redesign principles that make changes in elements of the SC scenario.

Similar to the classification of risk responses in Waters (2007) we consider two groups of redesign strategies: disturbance prevention and disturbance impact reduction. *Disturbance prevention* aims for the reduction of disturbance frequencies and its sizes i.e. acting in advance in order to eliminate, avoid or control any direct cause of disturbances (which can be any source of vulnerability). The *reduction of the impact of a disturbance* to robustness of SC performances implies a change of the characteristics of the SC scenario elements, such as using buffer stocks or increasing process flexibility. The use of the second group of strategies usually applies when disturbance prevention is impossible as one cannot act on the identified vulnerability source, or when prevention requires a large investment. This classification helps us to determine at the higher conceptual level what kind of response to use for a particular class of disturbances. However, the selection of particular redesign strategy depends on the *impact of disturbance to performance robustness, characteristics of the SC scenario and vulnerability sources.*

Within each group of redesign strategies, in line with the work of Van der Vorst and Beulens (2002), we classified and coded the redesign principles related to the element of the SC scenario that is influenced the most by its implementation. In Table 3.3 we present 14 redesign principles aimed at disturbance prevention and in Table 3.4 we present 16 redesign principles aimed at impact reduction and classify them according to the elements of SC scenario (e.g. GP – Managing system, Preventive redesign concept; DR – Managed System, Reductive redesign concept). In both tables, within each principle, we listed examples of redesign strategies. Here, we have to mention that some of these principles can be used for both purposes (especially in the part related to information system and organization).

Table 3. 3. Overview of redesign principles aimed at disturbance prevention

Element of SC scenario	Redesign principles - Disturbance Prevention	
Managed system	**DP1: Adjust the structure of the supply chain** (van der Vorst, 2000; Waters, 2007)	
	- Reduce the length of the supply chain	- Change the location of facilities
	DP2: Use product management (Waters, 2007; Melnyk et al. 2009)	
	- Avoid risky products - Plan component/material substitution	- Rationalize the product range
	DP3: Use technical solutions for performance monitoring (e.g. temperature, humidity, etc)	
Managing system	**GP1: Invest to avoid or reduce exposure to vulnerability sources** (Tang, 2006)	
	- Regular replenishment of equipment, vehicles - Economic supply incentives to cultivate additional suppliers	- Innovations (e.g. to packaging, information system, etc.) - Increase capacity
	GP2: Control variability (Zsidisin et al., 2000; Tang, 2006a; Waters, 2007; Hopp, 2008, Simangunsong et al., 2008; Simchi-Levi et al., 2008; Dani, 2009)	
	- Careful supplier selection process by using vendor rating techniques; supplier audits and quality certification programs - Use (virtual) pooling: centralization of decisions - Increase price stability - Sell products to various markets	- Use standardized work (procedures) - Use procedures and techniques to improve quality control, as well as industry standards - Develop proactive maintenance - Use demand postponement strategy
	GP3: Use revenue management strategies (Tang, 2006; Simchi-Levi et al., 2008)	
	- Use dynamic pricing (convenient for perishable products)	- Use promotion
	GP4: Decrease lead time (Waters, 2007)	
	GP5: Use short term forecasts or aggregate forecasts (Waters, 2007)	
Information system	**IP1: Use IT to increase data accuracy and speed and support decision making** (van der Vorst, 2000; Shukla and Naim, 2007; Hopp, 2008; Simchi-Levi et al., 2008; Simangunsong et al., 2008)	
	- Implement real-time information systems - Use the same information standards - Use techniques for automatic disturbance detection	- Use Tracking and Tracing system - Use DSS for production planning and scheduling, inventory management, demand management, …
	IP2: Create support for information transparency in the supply chain (van der Vorst, 2000; Zsidisin et al., 2000; Waters, 2007; Hopp, 2008)	
	- Insure infrastructure to enable information exchange and sharing	
	IP3: Collect relevant data about disturbances (e.g. Hopp, 2008)	
	- MTTF (mean time to failure), MTTR (mean time to repair), Variances in lead times	
Organization	**OP1: Increase collaboration in supply chain** (Zsidisin et al., 2000; Tang, 2006; Waters, 2007; Simchi-Levi et al., 2008; Hopp, 2008; Ritchie and Brindley 2009)	
	- Use information sharing - Joint forecasts and planning - Develop Supply Chain Risk Management	- Establishment of strategic alliances, such as transport alliances, VMI, etc
	OP2: Increase cooperation and coordination between departments (Waters, 2007)	
	- Closer cooperation between people who are doing planning and people who execute plans	
	OP3: Create an adaptive supply chain community (van der Vorst, 2000; Zsidisin et al., 2000; Waters, 2007; Simchi-Levi et al., 2008)	
	- Establishment of risk mitigation plans together with suppliers	- Align objectives and define KPIs
	OP4: Improve human resource management	
	- Select experienced workers	- Ensure proper training of employees

Table 3. 4. Overview of redesign principles aimed at reducing the impact of the disturbance on robustness of performances

Element of SC scenario	Redesign principles - Disturbance Impact Reduction
Managed system	**DR1: Adjust the structure of the supply chain** (Zsidisin et al., 2000; Snyder et al., 2006; Tang, 2006; Tomlin, 2006; Waters, 2007; Melnyk et al. 2009) - Increase the width of the supply chain - Use multiple modes of transportation
	DR2: Buffering in capacity and inventory (Zsidisin et al., 2000; Snyder et al., 2006; Tomlin, 2006; Waters, 2007; Hopp, 2008; Simangunsong et al., 2008; Simchi-Levi et al., 2008; Melnyk et al. 2009) - Increase number of equipment, vehicles or workers - Increase capacity of equipment, vehicles or space - Make strategic (safety) stocks - Make well stocked supply pipeline
	DR3: Increase flexibility of the supply chain (Tang, 2006; Tomlin, 2006; Waters, 2007; Hopp, 2008; Simangunsong et al., 2008) - Use multiple modes of transportation - Use flexible automation - Use temporary workers - Use multiple purpose resources (e.g. standardized equipment, vehicles, cross-trained employees)
	DR4: Use product management (Tang, 2006/a; Waters, 2007;Hopp, 2008; Simangunsong et al., 2008) - Use possibilities of product substitution, e.g. silent product rollover - Use product postponement
	DR5: Use of technical solutions to deal with disturbances (alarms, fire distinguishers, etc)
Managing system	**GR1: Hedging** (Tang, 2006; Tomlin, 2006; Waters, 2007; Hopp, 2008) - Using business disruption insurance - Diversifying operations across multiple markets - Produce certain products in-house and outsource other products
	GR2: Make back up options (Snyder et al., 2006; Tang, 2006; Tomlin, 2006; Waters, 2007; Hopp, 2008, Simchi-Levi et al., 2008) - Use a flexible supply contracts for non-strategic components, such as: Long term contracts (forward or fixed commitments contracts), Flexible or Option contract, or Spot purchase - Use alternative suppliers - Make alternative transport routes - Prepare backup for emergency supply
	GR3: Increase flexibility of planning and control (van der Vorst, 2000; Fleischmann et al., 2005; Tang, 2006, 2006a; Waters, 2007; Hopp, 2008; Melnyk et al. 2009) - Increase manufacturing flexibility, e.g. use flexible receipts, coordinate and redesign policies - Use postponement - Use event driven planning (update after event) - Do tasks parallel instead sequential - Allow time and capacity buffering in plans and operations - Use component/material substitution
	GR4: Use lead time management (van der Vorst, 2000; Tang, 2006; Waters, 2007; Simangunsong et al., 2008)
Information system	**IR1: Use IT to increase speed of disturbance detection and support decision making** (e.g. Zsidisin et al., 2000; Shukla and Naim, 2007; Melnyk et al. 2009) - Statistical process control - Data mining
	IR2: Create support for information transparency in the chain (e.g. van der Vorst, 2000; Zsidisin et al., 2000; Lee, 2002; Waters, 2007; Hopp, 2008; Simchi-Levi et al., 2008; Simangunsong et al., 2008) - Implement real-time information systems - Insure infrastructure to enable information exchange and sharing - Enable continuous data exchange with partners in the supply chain
	IR3: Use feedback loops (e.g. Disney et al, 1997)
Organization	**OR1: Increase preparedness to disturbances** (e.g. Hopp, 2008) - Enable empowerment (authorization of employees to make independent decisions) - Build awareness for crises situations
	OR2: Increase collaboration in chain (e.g. Zsidisin et al., 2000; Tang, 2006; Simchi-Levi et al., 2008) - Establish strategic alliances
	OR3: Create an adaptive supply chain community (e.g. Tang, 2006; Simchi-Levi et al., 2008) - Establishment recovery planning systems along the chain
	OR4: Use risk sharing supply contracts for strategic components (e.g. Tang, 2006, 2006a; Simchi-Levi et al., 2008; Hopp, 2008), such as: - Revenue sharing contracts - Back-up (advance purchase) contracts - Quantity flexibility contracts - Wholesale price contracts - Sales rebate contracts - Capacity reservation contracts - Cost sharing contracts - Buy-back contracts

3.3.4 Application of the research framework

Now that we have formulated the framework, it is important to describe the dynamic process of using it. Figure 3.3 presents an overview (partly based upon the Process Failure Modes and Effects Analysis - PFMEA method (see Scipioni et al, 2002), which is applicable for our research framework).

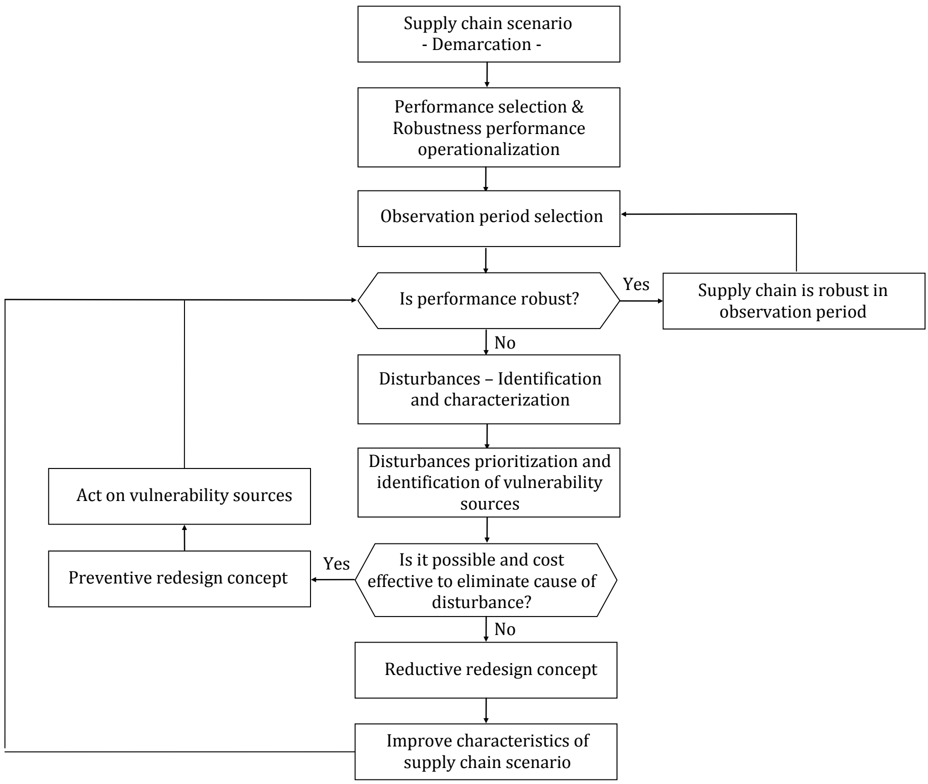

Figure 3. 3. Application of the research framework

For a selected case, it is necessary to describe the elements of the SC scenario and their characteristics, as well as boundaries of analysis. Here, the main element is the identification of the most important KPIs for the company and its SC and the operationalization of the robustness range. In the case study, for a specified length of the observation period, the performance on its KPIs can be assessed resulting in insight on the SC's or company's vulnerability. The existence of vulnerability periods indicates the presence of disturbances in logistic processes.

Possibilities for disturbances detection represent one of the major elements that drive the selection of redesign principle and strategies. Disturbance detection depends on the characteristics of the process, as well as on the decision of the management to monitor and trace disturbances in the SC. For that purpose, various techniques could be used, such as Data mining and Statistical Process Control (Shukla and Naim, 2007). In our work, based on the company's documentation and on interviews with employees, for each vulnerability period disturbances in logistic processes are identified, characterized and their impact on SC performances is assessed (see Section 3.1. in this chapter).

That way it is possible to rank disturbances and roughly indicate the level of vulnerability of the SC or the company under consideration. For the disturbances with the highest frequency and impact it is necessary to identify the main causes that may lead to them (i.e. vulnerability sources) and to assess all possible redesign strategies. It is clear that first attention should be given to redesign principles aimed at disturbance prevention (as this removes the problem), and next to principles that reduce the impact of the disturbance. In the end, a cost-benefit analysis of the most interesting redesign strategies should result in the selection of the best strategy.

3.4 Case study

To test the research framework we applied it to a case in the meat processing industry in the Netherlands. We performed data collection in the period from September 2008 till September 2009. The data is collected through several visits and student internships at a focal company that processes the meat as well as at a cold storage and a transportation company that takes care of the delivery of raw materials and the storage and distribution of final products. Data sources used are available reports, observations, as well as semi-structured interviews with the company directors and the operations and logistics managers. The data obtained is validated and checked with insights obtained in an earlier broader case study of the European meat SC (in Wognum et al., 2009).

In this section, we first briefly present relevant characteristics of the SC scenario and define the performance robustness for one selected KPI. Further, in line with the framework, we present an approach to identify and to rank disturbances, their characteristics, as well as a way to choose redesign strategies that may help to achieve performance robustness and reduce SC vulnerability.

3.4.1 Main elements of SC scenario and performance robustness assessment

The focal company is a company for meat slicing and processing. Upstream in the SC are slaughterhouses (suppliers) and farmers. Downstream are service providers (cold storage and transportation companies) and other meat processors (customers), retail distribution centres and outlets that buy packed meat products. The focal company works together with a logistics service provider (strategic partner) that manages transport and warehousing for the focal company (Figure 3.4).

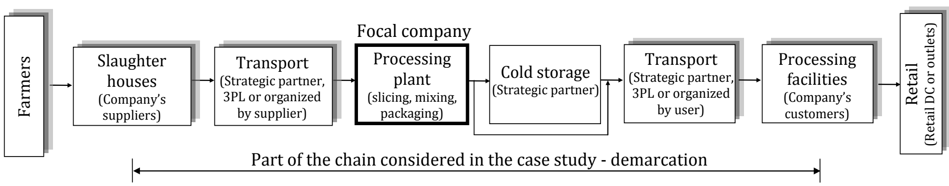

Figure 3. 4. The meat SC

The *logistical objective* of the company is to maximize the company's gross profit while maintaining a high customer service level. According to the company's managers, the company shows a *robust performance in profit* if the *operational gross profit is equal or greater than the value of the fixed overhead costs.* For example consider Figure 3.5 which shows that the values of the operational gross profit (as recorded once a day) is fluctuating over time and sometimes drops below a lower level (LL) of the robustness range. In periods in which the gross profit is below the lower level the company is vulnerable as the gross profit suffers from one or more disturbances in some logistic processes. Periods in which values of the operational gross profit are in the robustness range (that is above the lower level) are called robust periods (with respect to the KPI operational gross profit).

In Figure 3.5 multiple robust periods and non-robust periods are observed over the given observation period. This implies that the company's vulnerability (with respect to the KPI operational gross profit) is caused by one or more unexpected events that affect the logistic processes. The impact of disturbances is displayed by the length and the depth of each non-robust period. The largest shadowed part indicates a failure that was rapidly resolved (within 24 hours).

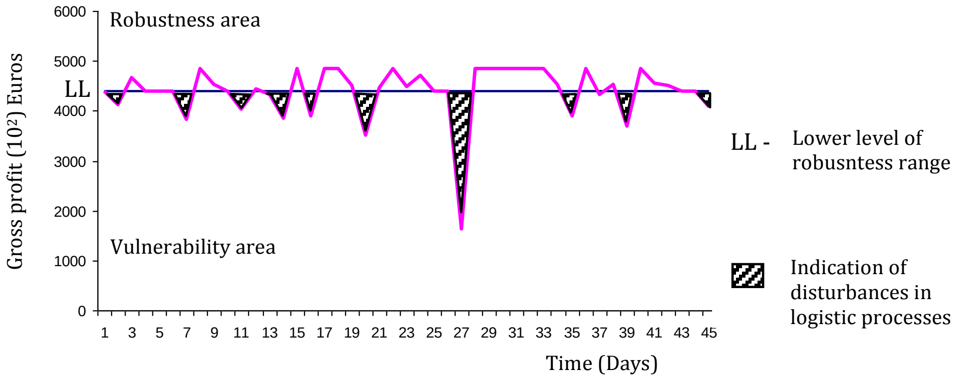

Figure 3. 5. Performance assessment – an example

3.4.2 Disturbances in processes and vulnerability sources

To find out what kind of disturbances are causing vulnerability, the research team conducted process mapping and logistic processes analysis. As a result, the main logistics processes were identified as well as the following disturbances: inventory shortage (raw materials), inventory obsolescence (final products), low utilization of raw material, low line productivity and low quality of final products. For each disturbance, we defined corresponding indicators and diagnosed the characteristics of the disturbance (Table 3.5) based on company data and interviews with logistic managers.

We constructed an influence diagram (Figure 3.6) to trace the vulnerability sources that caused the disturbances and to consider the interactions between processes.

For example, production planning and control, as well as inventory management decisions are mainly based on subjective judgment and experience of the manager (classified as GC2, Figure 3.2). This characteristic of the managing system results in sub-optimal decisions, which may cause disturbances such as: stock-outs of raw material, the piling of final products in stock and their obsolescence, as well as low a line productivity. The lack of an advanced decision support system for production planning and inventory management (IC1) causes decentralized subjective decision making.

To structure the analysis we rank disturbances according to their impact on gross profit.

Table 3. 5. Disturbances and their characteristics

Cate-gory	Process/Disturbance (D)	Indicator		Disturbance characteristics		
				Size	**Impact**	**Frequency**
Quantity	**Production** D1: Low utilization of the raw materials	Percentage of production waste	D11	Minor deviation: Parts of items	Low	Very frequent (every day)
			D12	Major deviation: Complete items	Medium	Occasionally (once per two month)
	Inventory management D2: Lack of raw material (Stock-outs)	Number of periods out of stock	D21	Major deviation: Several hours	Medium	Rare (few times per year)
			D22	Failure: Several days	High	Very rare (once per few years)
Quality	**Production** D3: Low quality of the final product	Products returned	D31	Major deviation: Part of shipment	Medium	Frequently (several times/month)
			D32	Failure: Entire shipment	High	Very rare (once per few years)
	Inventory management D4: Obsolete and damaged products in stock	Number of obsolete and damaged products	D41	Major deviation: Item level	Medium	Occasionally (once per three months)
			D42	Failure: Entire batch	High	Very rare (once per few years)
Time	**Production** D5: Low line productivity	Duration of idle time	D51	Major deviation: Several hours	Medium	Rare (few times per year)
			D52	Failure: Several days	High	Very rare (once per few years)

The disturbances are characterized based on the manager's experience and judgment, supported by documentation and other data sources (where possible). Evaluation and ranking is done according to the principles of PFMEA. At a scale from 1 to 10, the highest value (10) is assigned to the greatest impact of disturbance and to the highest frequency, and the lowest value to the disturbance with the least impact and a very rare frequency.

The detection of some disturbances in this case, happens actually during the production process and they get a low rank (easily detectable disturbances: D1, D2, D5). Other disturbances (D3 and D4) are more difficult to detect - they are detected upon a customer complaint or by control procedures (e.g. periodic inventory control). The more difficult to detect disturbances are ranked higher. The multiplication of the rank values related to the impact, frequency and detection results in the, what we call, Disturbance Priority Number (DPN). The higher the value of DPN, the higher the vulnerability level is. For a disturbance with a high DPN value one should try to explain why the DPN value is that high by analysing the (source of) vulnerability. This helps in identifying appropriate actions, i.e. redesign principles and particular strategies. Based on DPN, we categorized disturbances in three groups and redesign options:

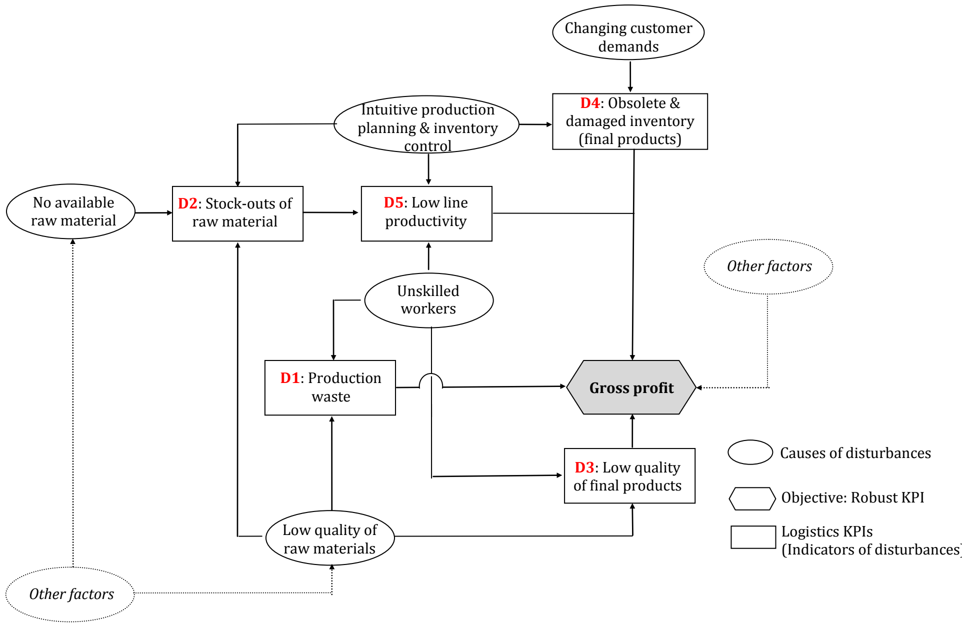

Figure 3. 6. Influence diagram of main logistic KPIs to gross profit

- Disturbances that have a light impact on gross profit (D11, D21, D51) are acceptable by management;
- Disturbances that have a medium impact on gross profit require operational solutions and process improvements (D12, D41);
- Disturbances that have a high impact on gross profit require thorough analysis in order to prevent them or to reduce their impact (D22, D31, D32, D42, D52).

In order to test our framework, we focus on one of the disturbances that influences gross profit the most: a low quality of final products (D31, D32) that result in product returns from customers. Based on interview data and analysis of database that contains data on customer complaints and other data as required by HACCP, we identified the main sources of vulnerability and classified them according to our classification scheme (presented on Figure 3.2). We present our findings as a causal diagram in Figure 3.7. It shows two main sources of vulnerability that cause a low quality of final products: low quality of raw material (belong to DC2 type of vulnerability source) and unskilled workers (belong to OC4 type of vulnerability source). Low quality of raw material is represented by four relevant characteristics:

lack of product freshness, high bacterial level, bad organoleptic properties, and undesirable structure (number of relevant characteristics is given presented as a number between brackets on the Figure 3.7).

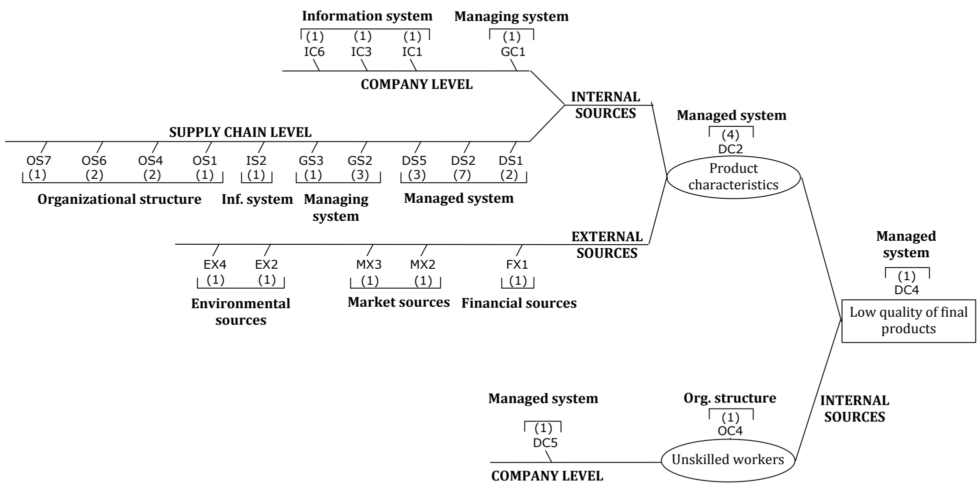

Figure 3. 7. Causal diagram: Main sources of vulnerability that causes a low quality of final products (abbreviations according to classification scheme presented in Figure 3.2; number represents number of relevant characteristic of each source).

The low quality of raw material is mainly a consequence of vulnerability sources at the SC level, which are partially controllable by management of the focal company. In total, we found 32 specific causes that may lead to this problem. Most of them (9) belong to product related hazards (DS1: metal or plastic residues in parts of meat) and heterogeneous quality of raw material (DS2: aspects such as lack of freshness, high bacterial level, frozen products, bad organoleptic characteristic, various size, structure and weight of items). These groups of vulnerability sources indicate a low level of quality control at suppliers, as well as equipment problems or an infrastructural problem at the supplier site (DS5: failure of cooling system, production line or mistakes of machine settings). These sources amongst other decrease the delivery reliability of suppliers (GS2), as well as of the logistics service provider. The last 6 causes are related to contractual issues (OS1), i.e. to a low level of cooperation and coordination in the SC (OS4), to low skills of workers at supplier (OS6) and to silo mentality (OS7).

At the company level, we identified four controllable sources of vulnerability: limited control actions (GC1) originating from technological constraints (such as: proper quality control directly at a production line), information system constraints: lack of an adequate information system to record and detect quality problems of input material (IC3, IC6) as well as a decision support system to assess the influence of quality problems on operational gross profit (IC1). However, we also identified a number of non-controllable sources of vulnerability, such as market price fluctuation (FX1), variability in availability (MX2) and quality of raw materials (MX3), as well as biological factors (such as animal diseases – EX2) and accidental events (EX4) such as traffic accidents that cause long delays. In the meat industry and food industry in general, especially in processing phases, the quality of final products depends to a certain extent on the health and skills of workers involved. Sources of vulnerability related to this problem are mostly company related, and they result from a need for additional, temporary flex-workers (DC5) and their lack of experience and training (OC4).

3.4.3 Selection of redesign strategies

According to our framework, there are two possible approaches: Either use redesign principles that aim to prevent the disturbance to happen, i.e. to reduce the number and frequency of product returns due to quality flaws, or those that aim to reduce the impact of the disturbance on operational gross profit.

The Preventive Concept requires analysis of vulnerability sources, where the goal is to eliminate them or reduce exposure of the company to them. Therefore, for each source of vulnerability described in the previous section, depending on their controllability level (Section 3.2 in Chapter 3) we identified corresponding redesign principles and strategies. The results of this analysis are presented in Table 3.6.

Trying to reduce exposure to vulnerability sources requires changes in the Managing System in order to increase the flexibility of the system. In the case that preventive strategies are too expensive or impossible to implement, the company could resort to the reductive strategies presented in Table 3.7. For example, using principles DR4 and GR1 result in an improved Demand Management, while GR3 results in possibilities to reduce the costs of product returns. In the end, use of IR1 principle could lead to the better disturbance management and improved decision making in critical situations.

Table 3. 6. Redesign principles and strategies aimed at disturbance prevention for identified vulnerability sources (shaded area indicates controllable sources of vulnerability)

Vulnerability source	Managed system (DP)		Managing system (GP)		Information system (IP)		Organizational structure (OP)	
	Principle		Principle		Principle		Principle	
DC2	DP3	Technical solutions	/	/	/	/	/	/
DC5	/	/	/	/	IP1	Advanced DSS	OP4	Training for employees; certificates
GC1	/	/	GP2	Advanced procedures (QC)	/	/	/	/
IC1	/	/	/	/	IP1	Advanced DSS	/	/
IC3	/	/	/	/	IP1	Advanced DSS	/	/
					IP3	Collect data	/	/
IC6	/	/	/	/	IP1	Advanced DSS	OP2	Increase cooperation
OC4	/	/	/	/	/	/	OP4	Training for employees; certificates
DS1	/	/	GP2	Supplier selection	/	/	OP3	Align objectives and KPIs
			GP2	Quality certification programs				
DS2	/	/	GP2	Supplier selection	/	/	OP3	Align objectives and KPIs
			GP2	Quality certification programs				
DS5	/	/	GP2	Supplier selection	/	/	OP3	Joint mitigation plans
GS2	/	/	GP2	Supplier selection	/	/	OP3	Align objectives and KPIs
GS3	/	/	/	/	/	/	OP1	Make strategic alliances
IS2	/	/	/	/	IP2	Information sharing	/	/
OS1	/	/	/	/	/	/	OP1	Make strategic alliances
OS4	/	/	/	/	/	/	OP3	Align objectives and KPIs
OS6	/	/	/	/	/	/	OP4	Training for employees; certificates
OS7	/	/	GP2	Supplier selection			OP1	Make strategic alliances
							OP3	Align objectives and KPIs
FX1	/	/	/	/	/	/	/	/
MX1	/	/	/	/	/	/	/	/
MX3	/	/	GP1	Multiple suppliers	/	/	/	/
EX2	/	/	GP1	Multiple suppliers	/	/	/	/

Table 3. 7. Redesign principles and strategies within Disturbance Impact Reduction Concept

	Redesign strategies – to reduce impact of a disturbances
Managed system	**DR4: Use product management** - Use possibilities of product substitution (offer another product to customers)
Managing system	**GR1: Hedging** - Using business disruption insurance - Diversifying operations across multiple markets (find customers with higher level of tolerance) **GR3: Increase flexibility of planning and control** - Increase manufacturing flexibility, e.g. use flexible receipts - Use component/material substitution (if possible, reuse returned products in production)
Information system	**IR1: Use IT to increase speed of disturbance detection and support decision making** - Statistical process control - Data mining

The above analysis shows that each source of vulnerability can be related to multiple redesign principles, ranging from operational/tactical changes (such as training employees or diversifying operations) to strategic changes (such as alternative suppliers, acting on multiple markets or installing new decision support systems). When this analysis is done for all main disturbances, an overview is created of all vulnerability sources and possible redesign principles. By evaluating the impact of these principles on the vulnerability level as a whole (each principle has an effect on the occurrence and impact of multiple disturbances), management can decide upon those principles that together will result in the best effect; hence chose for specific redesign strategies. Mathematical and simulation modelling efforts can be used in this process to support the management in quantifying the expected impact of possible redesign strategies.

3.5 Discussion, conclusion and future work

In this chapter an integrated framework is developed that guides food companies in managing disturbances and in designing robust SCs. We defined SC robustness as the degree to which a SC shows an acceptable performance in (each of) its KPIs at various levels of disturbances. More particular, a SC is robust with respect to a KPI if the value of that KPI, adequately measured over an observation period, is sustained in a predefined desired range, even in the presence of disturbances.

Our framework consists of the following steps: (1) the description of the SC scenario, and the identification of KPIs; (2) the identification and characterization of unexpected events and disturbances in processes that impact the performance robustness; (3) the assessment of performance robustness; (4) the identification of sources of vulnerability; and, (5) the identification of appropriate redesign principles and strategies. We have discussed the relationship between the elements of the framework and we have applied and tested the framework in an explorative case study. The results confirm that by analysing the performance robustness of specific scenarios we can detect and typify disturbances. For each disturbance found, we identified a set of vulnerability sources that can represent a direct or indirect cause of the disturbance. Then, per vulnerability source a set of redesign principles and strategies were identified to prevent the disturbance itself. Alternatively, if that is not possible or cost effective, a set of redesign principles and strategies can be used to reduce its impact of disturbance to other processes in the company or SC members (domino effect).

The chapter contributes to a better understanding of the concepts of vulnerability and robustness and of related issues in food SCs. Moreover, here we synthesize and integrate relevant papers on SC vulnerability and SC robustness. From a practical point of view, the involved managers of the company concluded that the research framework supports the analysis of SC's robustness and vulnerability, and helps in finding and categorizing disturbances, vulnerability sources and appropriate redesign principles and strategies. However, more research is needed to extend and validate our findings. On the one hand more case studies could be done within the food industry to be able to construct generic overviews of sources of vulnerability and redesign strategies. On the other hand, in order to select the most appropriate redesign strategies for sources of vulnerability and disturbances identified in the case, more research is needed that models and quantifies the impact on key SC performance indicators for alternative SC scenarios.

Acknowledgement

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4. The use of disturbance management principles to decrease vulnerability in fresh food supply chains– empirical findings

This chapter is based on the article prepared to be submitted to an international journal:

Vlajic, J.V., van der Vorst, J.G.A.J., and de Leeuw, S.,

"The use of disturbance management principles to decrease vulnerability in fresh food supply chains– empirical findings",

In this chapter we answer Research Question **3**:

What is the relationship between the contextual factors of food SCs and the use of disturbance management principles?

Abstract

The desire for more robust supply chains (SCs) has led to a growth in theoretical and practical interest in the application of both preventive and impact reductive disturbance management principles (DMPs). The application of these principles is found to be highly context dependent. We identified products, processes, SC networks and SC environments to be the contextual factors that influence the application of DMPs. Three case studies of fresh food SCs were conducted. For these, we collected data on the relevant disturbances, contextual factors, and particular DMPs applied. We observed that the contextual factors of products and the SC environment impose unavoidable constraints for application of DMPs on the whole SC scenario. The SCs respond to these disturbances by applying the DMPs to the process and SC network contextual factors. Most significantly, both preventive and impact reductive DMPs are more likely to be applied either to processes to cope with requirements due to product characteristics or to SC network characteristics to cope with requirements arising from business environment characteristics. We also analyse the circumstances that favours the use of particular DMPs. We formulate propositions from our findings and present them within conceptual models that depict the relationships between the contextual factors and the use of preventive and impact reductive DMPs.

Keywords: robust supply chains; assurance and reliability systems; proactive control, analysis and monitoring; disturbance prevention and risk management culture; redundancy; flexibility; information visibility; responsiveness

4.1 Introduction

The recent research and industry emphasis on supply chain management (SCM) aimed at increasing efficiency and leanness has resulted in supply chains (SCs) that are more vulnerable to disturbances (Stecke and Kumar, 2009; Vlajic et al. 2012a). Vulnerable SCs are less consistent in their performance, i.e. are less robust (Kleindorfer and Saad, 2005; Dong, 2006). SC robustness refers to the ability of companies to avoid and successfully manage disturbances along their SCs (cf. Tang, 2006; Stecke and Kumar, 2009). These companies are able to predict and detect relevant disturbances in their processes, to respond fast and to redesign their SCs quickly (cf. Blackhurst et al. 2005).

In recent SCM literature more and more research papers appear on the topic of SC vulnerability. According to Waters (2007) SC vulnerability is the exposure of a SC to a disturbance arising from the risks of operations within each organisation, of interactions within the SC, and from the external environment. One stream of research on SC vulnerability is mainly focused on the characteristics and categorisation of disturbances (e.g. Svensson 2000; Christopher and Lee, 2004; Christopher and Peck, 2004; Blackhurst et al. 2005; Peck, 2005; Viswanadham and Gaonkar 2008; Stecke and Kumar 2009). The other stream of research is mainly focused on response concepts and principles in general (e.g. Simchi-Levi at al. 2002; Christopher et al., 2006; Hopp, 2008) or on specific redesign strategies used to deal with uncertainty, risks of specific events or a selected disturbance (e.g. Tang, 2006, 2006a; Tomlin, 2006; Manuj and Mentzer, 2008; Cristopher et al. 2011). From this literature it becomes clear that different disturbances may have similar consequences for an SC (cf. Stecke and Kumar, 2009), and that the same response principles or redesign strategies may have different consequences for different SCs (Hallikas et al., 2004). In the first case, both a machine failure at a supplier’s plant and a traffic accident that seriously delays a delivery vehicle may result in an inventory shortage at a customer location. In the second case, a common redesign strategy is to use inventory to buffer against surges in demand or disturbances in supply. In the oil or automotive industry this buffering may only result in slightly higher warehousing cost, but in the fresh food industry the very same way of buffering may result in large quantities of obsolete product and the need to make product write-offs (Apte, 2010).

In fresh food chains the use of common redesign strategies against disturbances, such as buffering (Giunipero and Eltantawy, 2004; Hopp, 2008), sourcing from multiple suppliers (Giunipero and Eltantawy, 2004; Tang, 2006) and improving responsiveness (Chopra and Sodhi, 2004) is more complex due to the subtle but important characteristics of perishable products (Roth et al, 2008), its processes and the characteristics of the supply and demand market (Matopoulos et al., 2007; Christopher et al. 2011). Short shelf life of fresh food products, sensitivity to temperature shocks or light, biological activity, etc. contribute to complexity in planning and managing logistics flows. Amongst other things, logistics planning should be based on strict time constraints and there is a need for special conditioned containers to manage cold chains (cf. van der Vorst and Beulens, 2002). If not managed properly, companies may suffer from the high cost of inventory shortages or product write-offs. To illustrate this, Munelly et al. (2010) present the case of Marks & Spencer, a company that has implemented preventive practices to avoid wastage of fresh food products. By using "skin packs" for fresh meat products, the company reduced the packaging weight by 69%, increased shelf life of the product by 5 days, reduced procurement costs and producer's responsibility fees.

The literature implies that the use of disturbance management principles (DMPs) and specific redesign strategies depends on contextual factors (Manuj and Mentzer, 2008) related to the characteristics of particular chains. To the best of our knowledge no research paper has been devoted to investigating the relationship between specific contextual factors of food SCs and the use of the specific DMPs. Therefore, the objective of this chapter is to contribute to the body of knowledge in SCM literature by investigating the relationships between fresh food chain related contextual factors and the use of DMP to deal with disturbances and thereby reduce SC vulnerability.

The chapter is structured as follows. In Section 4.2 we present a research framework, and we focus on the two elements of the model: disturbance response concepts and contextual factors related to a food SC. In Section 4.3 we present case studies – first we explain data collection and present contextual factors and the response concepts of three food SCs. We end this section with cross-case analysis. In Section 4.4 we discuss the findings and present the resulting conceptual model and propositions. In Section 4.5 we present conclusions and suggest directions for further research.

4.2 Research framework

Based on a literature review and Vlajic et al. (2012a), we developed a research framework (Figure 4.1.) to investigate the relationship between contextual factors and the use of DMPs that belong to the disturbance management concepts.

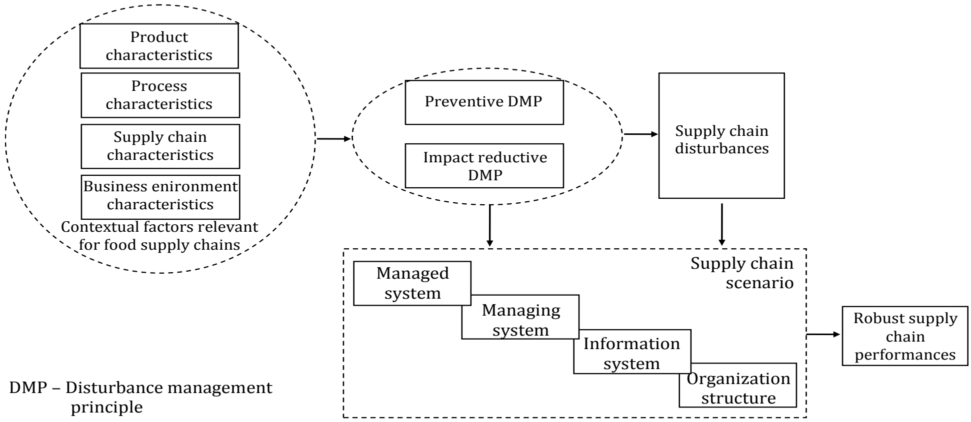

Figure 4. 1. Research framework for investigating the relationships between contextual factors and the use of DMPs

The SCM literature mentions different contextual factors that impact SC design and performance. For example, Olhager (2003) uses market, product and production characteristics as contextual factors to assess the position of the order penetration point in the SC. Luning et al. (2011) use four contextual factors to assess affected microbiological food safety output via control and assurance activities in food safety management systems, namely product, process, SC and SC environment factors. In this work, we follow this line of reasoning and use product, process, SC network and SC environment as contextual factors to assess SC susceptibility to disturbances due to constraints in the use of DMPs. These contextual factors represent specific characteristics of fresh food SCs that differentiate these chains from others. Product sensory properties, the need for particular certification for food suppliers, producers and processors (Luning et al. 2002), weather-dependent input from the fields, cold chain requirements, particular inventory constraints perishable products (van der Vorst, 2000) are just a few examples of specific characteristics of such food SCs.

As such, these contextual factors could create vulnerabilities in fresh food chains, which then influence the selection of DMPs. DMPs aim to manage disturbances by preventing them or by reducing their impact on SC performances. In the first case, preventive DMPs aim to reduce the frequency of disturbances by eliminating or avoiding their causes. When that is not possible, impact reductive DMPs are used, which aim to change elements of the SC scenario so that the whole system is less vulnerable to disturbances.

Here, a *SC scenario* can be defined as an internally consistent view of a possible instance of the logistics SC concept, i.e. the managed, managing, and information systems and organisation structure (van der Vorst, 2000). The *managed* system refers to the physical design of the network and a facility and all other elements that perform logistic activities (such as equipment, vehicles, and people), as well as inventory. The *managing* system refers to planning, control and co-ordination of logistic processes in the SC while aiming at realising strategic SC objectives and logistical objectives within the restrictions set by the managed system. The *information* system refers to information and decision support systems within each of the decision layers of the managing system (from annual to daily planning), as well as the IT infrastructure needed. The *organisation* structure refers to tasks, authorities and responsibilities of the departments and executives within the organisation and SC as well as the coordination of tasks in order to realise defined objectives.

In fresh food SCs performances typically reflect a time dimension (e.g. delays, stock-out time), a quantity dimension (e.g. quantity delivered vs. quantity ordered, surplus stocks) and a quality dimension (e.g. quality of products delivered vs. quality stated in specification, percentage of write-offs). All these KPIs have their cost equivalents (e.g. cost of stock-outs, costs of write-offs) and they might result in customer complaints and recalls (Luning et al. 2011). Successful disturbance management results in robust SC performances and overall SC robustness.

In Sections 4.2.1 and 4.2.2 we will elaborate more on the key elements of this research: contextual factors and DMPs.

4.2.1 Contextual factors of a food SC

In SCM literature, several publications argue that SC specificities, i.e. contextual factors, may influence SC vulnerability and determine the use of specific DMPs and strategies (Manuj and Mentzer, 2008). These contextual factors are mostly analysed by considering product and processes, the SC network or business environment (van der Vorst, 2000; Olhager, 2003; Reiner and Trcka, 2004; Zsidisin, 2003; Luning et al., 2011). In Table 4.1 we present an overview of the contextual factors and its characteristics that are mostly considered in similar research topics in the SCM literature. Next, we elaborate on each of them.

Table 4. 1. Contextual factors that may influence selection of DMPs

Contextual factors	Contextual characteristics	Author(s)
A (End) Product	A1. Shelf life	Luning et al., (2002, 2011), Van der Vorst and Beulens (2002)
	A2. Sensory properties	Luning et al., (2002)
	A3. Weight loss	Luning et al., (2002)
	A4. Assortment (SKU format)	Luning et al., (2011)
	A5. Customisation opportunities	Olhager (2003)
B Process	B1. Specialised resources for product transformation and storing	Van der Vorst (2000), Luning et al., (2011)
	B2. Fresh food inventory capacities	Van der Vorst (2000)
	B3. Timing constraints	Zsidisin (2003); Van der Vorst et al. (2005); Christopher et al. (2006)
	B4. Order characteristics	Zsidisin (2003)
	B5. Information systems that support product quality preservation	Mahalik (2009)
	B6. Information systems that support automatic processing or packing and labelling lines for food products	Du and Sun (2004); Bulut and Lawrence (2006); Panos and Freed (2007); Kondo (2010)
	B7. Food processing and logistics activities	Van der Vorst (2000); Luning et al., (2002)
	B8. By-products and return flows	Van der Vorst (2000); de Koster et al., (2002); van der Vorst et al., (2005)
C Supply chain network	C1. Supplier capacity constraints	Van der Vorst (2000); Zsidisin (2003)
	C2. Supply chain network structure	Cavinato (2004); Peck (2005); Jain and Benyoucef (2008)
	C3. Ensured product quality from supplier	Zsidisin (2003)
	C4. Sourcing strategy	Cavinato (2004); Wagner and Bode (2006)
	C5. Warning capability from the aspect of: Information exchange	Craighead et al., (2007)
	C6. Warning capability from the aspect of: Triggers for response actions	Craighead et al., (2007)
	C7. Supplier dependence	Wagner and Bode (2006); Giunipero and Eltantawy (2004)
	C8. Strategic partnerships	Matopoulos et al., (2007); Waters (2007)
D Business environment	D1. Market capacity risk	Zsidisin (2003)
	D2. Market characteristics	Van der Vorst (2000); Christopher et al. (2006)
	D3. Severity of stakeholders' requirements	Matopoulos et al. (2007); Luning et al., (2011)

4.2.1.1 Product characteristics

Fresh foods are generally considered as risky products (Speier et al., 2011) because of high perishability (cf. Van der Vorst et al., 2002), which can ultimately lead to product write-offs and food waste. Perishability can be seen through shelf life and sensory properties (e.g. colour, firmness, and aroma) (Luning et al., 2002). The shorter the shelf life and the greater the change in sensory properties, the more risky the product becomes. Next, in food SCs, quality is interconnected with quantity, i.e. a change in quality usually leads to quantity change as well (for instance, drip losses in meat products reduce the quality as well as the weight of the meat product, Papadima and Bloukas, 1999). Therefore, weight loss is another largely unavoidable characteristic of fresh food products, which might have an influence on response principles.

Product packaging is relevant for fresh food products because of the high risk of product contamination and spoilage (Luning et al., 2011), but it also contributes to increased product recognition and thereby product assortment. The customisation opportunity (Olhager, 2003) of the final food product is also identified as contextual factor due to its nature: for instance, fruit and vegetables can be customised from the ripening aspect and meat products can be customised (i.e. processed) in relation to the size of product, weight, meat/fat ratio, type of meat (e.g. shoulder, leg). As such, the customisation opportunity implies a potential for the use of various product delivery strategies (Olhager, 2003) and sales and marketing options.

4.2.1.2 Process characteristics

Contextual characteristics of processes in fresh food SCs could be described in a structured way by using components of a SC scenario on the process level.

At the process level, the *managed* system refers to fresh food, specialised processing facilities (e.g. for fresh meat, milk, salads, fruit processing) and equipment (e.g. cleaning, ripening, cutting lines and tools, as well as highly sophisticated capital-intensive machinery) to support transformation processes. Though product transformation is usually automated, certain processing activities are performed manually which may negatively affect product quality (Luning et al., 2011). The need for a controlled atmosphere along the chain (in storage facilities, during transport, production and processing, as well as in packaging) results from the perishable nature of the food products and the high risk of waste. Similarly, an inventory of fresh food also has to be kept in a temperature-controlled environment, the inventory level is dictated by shelf life, and storage buffer capacity is restricted by the capacity of special tanks or containers used (van der Vorst, 2000).

Setting and managing timing constraints (Van der Vorst et al., 2005), and realisation of purchasing activities are part of the *managing* system. *Timing constraints* are related to production throughput and lead times and they often limit control actions. Fresh food chains usually have long *production throughput times* (van der Vorst, 2000; Taylor, 2005) due to the nature of the product. Long *lead times* typically result from long distances and multiple delays in material flow (Chopra and Sodhi, 2004), and they contribute to increased SC vulnerability (Tang, 2006). For fresh food products, a reduction in lead time will reduce the risk of quality disturbances, such as those related to perishability (Roth et al, 2008). *Order characteristics*, such as changes in *volume and mix requirements* for delivery of final products result from seasonal supply and demand of food products. If a supplier cannot make appropriate increases for volume fluctuations or product mix requirements in the case of increased demand (Zsidisin, 2003) the SC might become vulnerable. In combination with limited production flexibility, vulnerability is even amplified.

At the process level *information systems* support the operational and tactical planning, as well as the control of production and logistic activities. For fresh food chains, the information system considers the support of setting, monitoring and analysis of parameters needed to maintain a) high quality products during product transformation, packing and labelling, storing, and b) high quality of customer service (on-time deliveries, fresh products on the shelves in retail outlets). For production and processing, information systems usually support automatic processing and packing lines, control and grading of fruits and vegetables (Du and Sun, 2004; Kondo, 2010), as well as sensor control, and temperature regulation that enable the preservation of fresh products. As an example, nano-sensors can be used for detecting pathogens and contaminants and even tracking and tracing the food in contrast to traditional tagging (Mahalik, 2009). In food retail systems, Point-Of-Sale systems, automatic data collection technologies (e.g. bar-code, RFID, voice or visual systems) are typically used (Panos and Freed, 2007). For logistics activities an information system needs to support transport, distribution and storing processes that should provide high-level customer service and at the same time it should support traceability (Bulut and Lawrence, 2006).

The *organisation structure* refers to tasks, authorities and responsibilities of the departments and executives within the organisation to realise food processing and logistic activities and achieve defined performance targets at a process level. Next to the need for skilled labour to perform the regular task of scheduling and organisation of food products flows, fresh food chains specifically need to handle by-products that typically result from production or processing activities (van der Vorst, 2000). Moreover, there is also a need to organise return flows (e.g. damaged products, logistics units), (de Koster et al., 2002; van der Vorst et al., 2005) which results in increased complexity of organisational structure on the process level.

4.2.1.3 Supply chain network characteristics

SC network characteristics could be described in a structured way by using components of the SC scenario on the network level.

Important characteristics for (fresh) food SC networks are *supplier capacity constraints* and *SC structure*. Fresh food SCs in general are characterised by variability of quality and quantity of supply of farm-based inputs (van der Vorst, 2000), as well as by specific processing technology. Consequently, the inability to quickly increase production output in times of increased demand (Zsidisin, 2003) represents a significant source of vulnerability. SC structure considers its length and width. Due to globalisation and specialisation, today's SCs are longer than ever before, and they are becoming leaner (Peck, 2005). Longer and more complex food SCs are more vulnerable (Jain and Benyoucef, 2008). However, in some situations long SCs cannot be avoided due to geographically determined supply base (e.g. sourcing of tropical fruits) and a limited number of suppliers. SC width is perceived conversely in comparison with SC length – the wider the SC, the more options for supply and horizontal collaboration.

In fresh food SCs, the managing system considers two important factors: *sourcing strategy* and supply of *ensured product quality* from supplier. There are a few typical supply strategies, i.e. single, dual or multiple sourcing. There has been a recent trend towards reducing the supply base and at the same time establishing closer relationships with the suppliers in the smaller supply base (Wagner and Bode, 2006). However, the smaller the supply base, the more difficult it is to find alternative suppliers in the case of key supplier failure or in the case of increased demands. According to Cavinato (2004) rationalisation of the supply base contributes to the vulnerability of the purchasing company. To ensure product quality (Zsidisin, 2003; Luning et al., 2002), checking and requesting valid supplier certification is a usual part of control and planning systems.

For fresh food chains warning capabilities that proactively or in a very short period of time signal disturbances are very important (c.f. van der Vorst et al., 2009; Li et al., 2010). *Warning capabilities* can be defined as the interactions and coordination of SC resources to detect a pending or actual disturbance and to subsequently disseminate pertinent information about the disturbance to relevant entities within the SC (Craighead et al., 2007). In modern SCs warning capabilities are often defined by the most powerful actor in the chain.

In organisational structure, types of relationship/collaboration between SC actors as well as integration are perceived as important for food SCs (Matopoulos et al., 2007) and they indicate the level of interaction between SC actors. Supplier *dependence* on buyer or other way around is another characteristic that increases the vulnerability of the dependent party, especially in the case of the limitations of the demand or supply market, respectively (Wagner and Bode, 2006), and high criticality of the purchased item (Giunipero and Eltantawy, 2004). A dependence relationship indicates the distribution of power in SC and highlights which company is acting as the most powerful stakeholder that might define business rules and disturbance management (cf. Luning et al., 2011). Another interesting relationship is related to strategic partnerships, especially outsourcing. The use of outsourcing in transport or distribution might be perceived as risky if a trusting relationship is not established (Waters, 2007).

4.2.1.4 Supply chain business environment characteristics (supply market)

Market capacity risk occurs when there are only a few supply sources available (Zsidisin, 2003), which is the case for highly perishable products where freshness requirements represent a constraint on supply sources (for example, in some phases in meat chains lead time is very short (2-3 days) due to freshness requirements, which poses constraints on selecting supplies that can make a delivery within this short time-frame). Moreover, next to available suppliers, having *capable, qualified, and certified suppliers* in the supply base is critical for executing a successful supply strategy (Zsidisin, 2003).

Fresh food SCs are characterised by seasonality in supply and demand, as well as by dependability of weather conditions (van der Vorst, 2000). These characteristics of supply and demand contribute to complexity of chain management with respect to their balance. As demands increase, organisations and their suppliers must be responsive to it or face the prospect of losing market share (Monczka et al., 2009). The same effect appears when disturbance in supply occurs.

Strict and differing requirements on product quality and availability set by stakeholders (e.g. governments, customers, non-profit organisations) put pressure on fresh food SC actors to use certain disturbance management principles. In the food industry, food quality and preservation are prescribed by product-dependent assurance systems, standards and recommendations (cf. Matopoulos et al., 2007).

4.2.2 Disturbance response principles (DMPs)

In general, the most common DMPs correspond to traditional risk management approaches and they are focused on risk and disturbance reduction by decreasing the probability/frequency of an occurrence or reducing the severity of consequences (Norrman and Jansson, 2004; Waters, 2007). In the literature, the first approach is known as cause-oriented, i.e. a preventive concept, and the second approach is known as effect-oriented, i.e. an impact reductive concept (Wagner and Bode; 2009; Vlajic et al., 2012a). In fresh food SCs both concepts are used (Table 4.2.). In the next two sub-sections we explain preventive and impact reductive disturbance management concepts (DMCs) and the corresponding DMPs in more detail.

Table 4. 2. Disturbance management concepts (DMCs) and principles (DMPs)

DMC	DMPs	Author(s)
P Preventive	P1. Assurance and reliability systems	Luning et al., (2002, 2011)
	P2. Proactive control, analysis and monitoring	Harland et al., (2003); Christopher and Lee (2004); Blackhurst et al., (2005); Peck (2005); Waters (2007); Stecke and Kumar (2009); van der Vorst et al., (2009, 2011); Li et al., (2010)
	P3. Development of disturbance prevention and risk management culture	Waters (2007); Simchi-Levi et al., (2008); Stecke and Kumar (2009)
R Reductive	R1. Redundancy	Rice and Caniato (2003); Chopra and Sodhi (2004); Blackhurst et al., (2005); Tang (2006); Wagner and Bode (2009); Stecke and Kumar (2009)
	R2. Flexibility	Wilson (1996); Gunaserkran et al., (2001); van der Vorst et al., (2005); Waters (2007); Stecke and Kumar (2009); Gualandris and Kalchschmidt, (2011)
	R3. Information visibility	Hallikas et al. (2004); Van der Vorst (2006); Stecke and Kumar (2009); Roth et al., (2008)
	R4. Organisational structure	Chopra and Sodhi (2004); Barker and Santos (2010); Wagner and Neshat (2010)

4.2.2.1 Cause oriented, preventive response concepts

Cause-oriented DMCs attempt to reduce the probability of the occurrence of a disturbance by addressing its causes; these concepts are preventive in nature (Lewis, 2003; Kleindorfer and Saad, 2005; Manuj and Mentzer, 2008; Wagner and Bode, 2009; Vlajic et al., 2012a). At first, causes of disturbances should be avoided, and that can be done in the design or planning stage of the SC. For example, companies can avoid delays, or at least prepare for them, by appropriately and economically placing and sizing their capacity and inventory reserves (Chopra and Sodhi, 2004). If avoidance is not feasible or desirable, the frequency of disturbances has to be reduced. In purchasing, for instance, goods inward inspections and multiple suppliers for the same sub-component are justified on the grounds of possible supplier failure (industrial action, fire, poor quality, etc.), (Lewis, 2003). Disturbance avoidance should precede disturbance reduction (cf. Kleindorfer and Saad, 2005). Lewis (2003) however, states that "complexity of causal events (most lying beyond the boundaries of the operation) and the variability associated with negative consequences may suggest that preventive DMC alone will never suffice because some events can never be predicted and some stakeholders will always perceive losses". The same author observed that too much reliance on prevention and mitigation control actually results in a less effective overall recovery.

Typical *cause-oriented, preventive DMC* that could be used to manage disturbances in the supply part of chains generally is related to supply risk management (Harland et al., 2003), and in the case of food products, to quality management (Luning et al., 2002). The main DMPs within this concept relevant for fresh food SCs are:

P1) *Assurance and reliability systems*, as a part of a general safety and security program, represent the framework for quality control (such as International Standard Organization – ISO). In the agri-food industry these systems represent a basis for controlling of food safety, health aspects and other quality aspects (Luning et al., 2002). Common assurance systems in the food industry are: the Good Practices (e.g. *Good Manufacturing Practice* - GMP, *Good Hygienic Practice* - GHP, *Hazard Analysis Critical Control Points* - HACCP) and combined systems (such as the *British Retail Consortium* - BRC). In fresh food SCs the *International Food Standard* (IFS) is often used, as well as country dependent food laws and standards (e.g. in the Netherlands, and for vegetable and fruit production *the Integrated Quality Assurance System* (IKZ – "Integrale KwaliteitsZorg" in Dutch), Luning et al., 2002).

P2) *Proactive control, analysis and monitoring*: Proactive control is based on consideration of SC risk management issues in the decision-making process, so that responses are planned in advance (Waters, 2007). Proactive control is usually applied when deciding about strategic sourcing practice, vendor rating programs, supply contracts, information sharing and integrating practices, as well as when monitoring suppliers and controlling any possible opportunistic tendencies (Harland et al., 2003). Decisions on a tactical (e.g. inventory management issues) and operational level (routing and scheduling issues), made while taking into account the risks involved, belong to the normal practices of good logistic management (Waters, 2007). Proactive control is based on different types of Decision Support Systems (DSS) (Blackhurst et al., 2005), which would enable making informed decisions regarding the merits of prevention strategies (Peck, 2005; Stecke and Kumar, 2009), tools based on statistical process control and control charts (Christopher and Lee, 2004), data mining (Li et al., 2010), intelligent web agents (Blackhurst et al., 2005) or expert systems. In the fresh food industry, DSSs are increasingly based on new concepts - QCL (*Quality Controlled Logistics*), (van der Vorst et al., 2011) and *Early Warning and Proactive Control Systems* (EW&PCS) combined with expert knowledge (Li et al., 2010). In fresh food SCs, these systems could also be used to estimate best-before-date (van der Vorst et al., 2009).

P3) *Development of disturbance prevention and risk management culture*, i.e. attitudes to quality and processes, by worker training programs (Waters, 2007) and by enhancing the visibility and coordination of activities in the SC (Stecke and Kumar, 2009). All actors in the SC should share a similar working culture and work towards the same objectives (Simchi-Levi et al., 2008). Here, objectives are related to prevention of disturbances when possible and trained responses and procedures when disturbance occurs.

4.2.2.2 Effect oriented, impact reductive response concepts

Effect-oriented DMC attempts to limit or mitigate the negative consequences of disturbances (Waters, 2007; Wagner and Bode, 2009), and this concept is also known as *impact reductive DMC* (cf. Kleindorfer and Saad, 2005; Vlajic et al., 2012a).

SCM literature indicates a few typical effect-oriented, impact reductive DMPs (Chopra and Sodhi, 2003; Simchi-Levi et al., 2008) that are also relevant for fresh food SCs. These DMPs are:

R1) *Redundancy* at the process level (inventory or time buffers, Wagner and Bode, 2009; increase in resource capacity, Rice and Caniato, 2003; Chopra and Sodhi, 2004; Blackhurst et al., 2005) and at the SC level (multiple locations, Stecke and Kumar, 2009; multiple suppliers, Rice and Caniato, 2003; Tang, 2006).

R2) *Flexibility*, considered as the ability of the system to adjust to any change in relevant factors like product, process, loads and machine or the ability to perform SC network reconfiguration by adopting various sourcing (Wilson, 1996) or transport options (Waters, 2007; Stecke and Kumar, 2009). At the process level, flexibility is typically increased by using postponement (Gualandris and Kalchschmidt, 2011), or flexible manufacturing systems (Gunaserkran et al., 2001; van der Vorst et al., 2005).

R3) *Information visibility*, which can be achieved by using specialised software to enable visibility, track and monitor disturbances (e.g. SC event management software – SCEM or Enterprise Resource Planning – ERP applications, Stecke and Kumar, 2009) or enable collaborative planning (Hallikas et al. 2004). A key factor in information visibility is information sharing. In the food industry, information visibility is related to tracking and tracing (Van der Vorst, 2006; Roth et al., 2008).

R4) *Responsiveness* to disturbances in logistics processes (Chopra and Sodhi, 2004; Barker and Santos, 2010), which should start as soon as an incident is detected, i.e. it refers to the speed of change. This is one of the key elements for the SCs highly exposed to risk. According to Wagner and Neshat, (2011) food SCs rank relatively high on the scale for risk exposure. To increase responsiveness, it helps if SCs have already adopted strategies to increase the speed of material flow, such as cross-docking or direct delivery from the supplier. Additionally, responsiveness can be increased by having additional supply sources, not only by reserving additional suppliers, but also by enabling transshipment (supply from the same echelon).

4.3 Case studies

In this research we used a case study approach to apply our research framework and identify relationships between contextual factors and the use of DMCs and DMPs. In this section, we first describe the case selection and data collection (4.3.1). Then we present the case findings (4.3.2) and cross-case analysis of our findings (4.3.3).

4.3.1 Data collection

To reduce extraneous variation and to clarify the domain of the findings we selected a population of large retail SCs that are doing business in the same business environment (Serbia). We used theoretical sampling to select cases from the population, as suggested by Eisenhardt (1989). As representative cases, we selected three fresh food SCs of leading companies in the retail sector. The fact that these companies have been extending their business in the last few years in a period of global crisis (opening new outlets and distribution centres) was an indicator of successful businesses and successful disturbance management.

To increase generalizability, we have chosen to differentiate cases according to product type (fruit and meat), sourcing (locally or internationally), product customisation point (at supplier or in the retail system), and product assortment (narrow and wide). We selected two products that are critical for retail systems: fresh meat and bananas. Both products have high demand levels during the year, and they are perceived as significant factors for increases in sales. Fresh meat has a high consumption rate because of its nutritional value. Bananas are available during the whole year and they have become a popular fruit that often replace domestic fruit due to its low price (e.g. despite the fact that apples are domestic fruits on the Serbian market, in 2010 1kg of bananas was cheaper than 1 kg of apples). The major appeal of banana as a fruit combined with its low price is used by retailers as a marketing ploy to attract customers.

Preparation and data collection was performed from October 2010 till June 2011. At the first meeting with the companies' authorities we explained the goal of our research and selected principle informants. To increase the validity of interviews, we selected retail SC managers with a logistics educational background and at least two years of experience in practice as principle informants. A case study protocol was sent to the selected principle informants and companies' authorities, and interviews were scheduled. We asked principle informants about disturbances in logistic processes, their causes, and ways they manage disturbances. Also, during the interview we identified contextual factors of the specific cases we investigated, i.e. we asked what factors influenced the use of specific DMPs. Each question was discussed and additional explanations of answers were written down. There were two interviews for each case – one interview to discuss questions and one interview to verify the data sheets of answers. Each interview lasted between three and four hours, and principle informants were contacted by phone or mail when additional insights were needed.

4.3.2 Case findings

We follow our research framework (Figure 4.1) in describing the selected cases. First we present contextual factors and then DMPs for each case.

- Contextual factors

Here we present the most important features of contextual factors regarding products and processes (Table 4.3) and SC networks and SC business environment (Table 4.4).

Details can be found in the case description in Appendix 4.1. These contextual factors will be later on be used in combination with the identified DMPs to investigate their mutual relationship in the selected cases.

- Disturbance management principles (DMCs)

Based on the classification of DMPs and redesign strategies (see Section 2.2), we categorised the data collected accordingly – in Table 4.5 we present a list of redesign strategies used that belong to preventive DMPs, and in Table 4.6 we present a list of redesign strategies used that belong to impact reductive DMPs used in the three cases.

Table 4. 3. Data matrix: product (A) and process (B) characteristics

Product (A) and Process (B) characteristics	Case 1: Bananas (unpacked)	Case 2: Fresh meat (unpacked)	Case 3: Fresh meat (pre-packed)
A1: Shelf life in retail system	3-5 days (ripe bananas)	3-4 days (after processing)	10 days
A2: Sensory properties (retail)			
a) Physical changes	Bruising; broken fruit, burst skins,	Bruising	No
b) Chilling injuries:	Brown stripes, no ability to ripen	Frozen products	Frozen products
c) High temperature exposure	"Cooked bananas"	Bad odour, spoilage	Spoilage
A3: Weight loss			
a) In retail	0.5 - 1%	0.5-1%	0-1%
b) Max loss	3% when humidity is too low	2% two days after slaughter	2% two days after slaughter
A4: Assortment			
In retail/ supply part of the chain	1 SKU/1 SKU	4-5 SKU/30 SKU	200 SKU/200 SKU
A5: Product customisation opportunity			
a) In retail system	In retail and supply part of the chain	In retail and supply part of the chain	In supply part of the chain
Managed system			
B1 Resources needed	Outlets: fruit zone Storage: Temperature controlled chamber Transport: Refrigerated container Production: plantation field	Outlets: Cold, closed shelves Storage: Cross-dock, cold storage Transport: Refrigerated trucks Production and processing: slaughter house, cutting and slicing equipment	Outlets: Cold, closed shelves Storage: cold storage Transport: Refrigerated trucks Production and processing: slaughter house, cutting & slicing equipment, packing line
B2 Inventory of fresh foods	Safety stock of green bananas	Buffers of meat parts in outlets and cross-dock warehouse	Zero inventory
Managing system			
B3:Timing constraints			
a) Timing defined by:	Transport options/limitations	Required freshness	Required freshness
b) Production throughput time	28-36 weeks	40 weeks	40 weeks
c) Order lead time	A few weeks to couple of months	Two days	One to two days
B4: Order characteristics:			
a) Volume requirements	Driven by transport chain arrangements	Fixed quantities	Fixed quantities
b) Mix requests by supplier	-/-	Production SKUs	No product mix requirements
Information system			
B5: Product quality support: Monitoring parameters:	Temperature; Humidity; Ventilation	Temperature; Humidity	Temperature; Humidity; Product-related information
B6: Logistics support	TMS; WMS	TMS; WMS	ERP, SRM
Organisational structure			
B7: Return flows/duty of			
a) By-products	No	Bones	No
b) Return or reverse flows	Banana boxes/retailer	Spoiled products, supplier and meat containers/3PL	Products out of specification/supplier
B8: Customization activities	In retail and supply part of the chain	In retail and supply part of the chain	In supply part of the chain

Table 4. 4. Data matrix: SC network (C) and SC environment (D) characteristics

SC network (C) and SC environment (D) characteristics	Case 1: Bananas	Case 2: Unpacked fresh meat	Case 3: Pre-packed fresh meat
Managed system:			
C1: Supplier capacity constraint	Influenced by weather	Defined by technology used in a factory	Defined by technology used in a factory
C2: Supply chain network structure			
a) Supply chain length	Long: Producer (plantation) – Foreign distributor – Port - Customs – Container ship - Port – Customs – Road transport – DC – Distribution – Retail	Short: Producer (farms) – Transporter - Processor (slaughter houses) - Transporter – DC - Distribution – Retail	Short: Producer (farms) – Transporter - Processor (slaughter houses) – Transporter –Retail
b) Retail system	343 outlets (three formats) and DC's ripening chamber	343 outlets (three formats) and DC's cross-dock cold warehouse	9 large outlets
Managing system:			
C3: Ensured product quality	Defined by retailer's specification	Certified supplier only	Certified supplier only
C4: Sourcing Strategy	Single sourcing – preferred supplier;	Dual sourcing regularly	Multiple sourcing
Information system			
C5: Warning capabilities - Information exchange			
a) Type	Delivery schedule, quantity (standardised)	Delivery schedule, quantity available	Delivery schedule, quantity, quality, packing
b) Frequency	By protocol or at the request of retailer	Information on disturbance – at risk and upon event	Available on request
C6: Warning capabilities - Triggers for response action			
a) Delivery: time delay	DC: Delay more than 72h Outlets: daily	DC: Later than 18.00h Outlets: later than 10.00h	Later than 13.00h
b) Delivery: quantity	Variation more than 2%	Variation more than 15%	Variation more than 5% per supplier in month time
c) Delivery: quality	5% of product out of specification per delivery	More than 10% of product out of specification per delivery	Less than 1/3 of the time till expiry date;
Organisational structure:			
C7: Supplier dependence	Transactional relations	Close cooperation between key supplier and retailer	Suppliers compete on the local market
C8: Strategic partnerships			
a) Distribution	3PL, priority customer	3PL, priority customer	-/-
b) Incoming transport	3PL	Performed by supplier	Performed by supplier
D1: Market capacity risk			
a) Supply base constraints	Only international suppliers	Only local suppliers	Only local suppliers
b) Qualified and certified suppliers	Multiple suppliers qualified, but not all of them certified	Around 10 large local suppliers	Around 10 large local suppliers
D2: Market characteristics			
a) Supply predictability	Uncertain quality & quantity	Uncertain quality & quantity	Uncertain quality & quantity
b) Demand predictability	To a certain extent	To a certain extent	To a certain extent
c) Demand seasonality/ peaks	Less demand in summer season	Three times higher demand over peak periods	Less demand in summer season
D3: Severity of stakeholder's requirements (retailers):			
a) Delivery window to DC	24h to DC	2h to DC	-/-
b) Delivery window to outlets: time tolerance	4h to retail outlets	4h to retail outlets	4h daily (2% out of spec./month)
c) Delivery: quantity tolerance	5% out of spec./month	5% out of spec./month	2% out of spec./month
d) Delivery: quality tolerance	5-10% of product out of spec. (ripeness of bananas)	10% of product out of spec. (freshness of meat)	Freshness & leanness of meat (2% out of spec. /month)

Table 4. 5. Preventive redesign strategies: overview of three cases in relation to preventive DMPs

Preventive principles	Case 1: bananas	Case 2: fresh meat	Case 3: fresh meat
P1: *Assurance and reliability systems*	- Phyto-sanitary control	- Veterinary certificate	- Veterinary certificate
	- HACCP, IFS[a] - Internal product and process quality control protocols - Standardised process control in retail system	- HACCP, IFS - Internal product and process quality control protocols - Standardised process control from suppliers to retail outlets - Use of reliable equipment, special meat containers and vehicles	- HACCP, IFS - Internal quality control standard (strict product quality, packing specifications, lead time) based on: IFS, GFSIb - Using reliable cooling system and back-up energy source
	- Internal product and process quality control requirements in retail system	- Internal product and process quality control requirements (suppliers, transport)	- Internal quality control requirements for suppliers: ISO 9001, GMP[c], GHP[d]
P2: *Proactive control, analysis and monitoring*	- Avoid purchase of ripe bananas - Plan frequent deliveries to outlets (once per week regularly, emergency delivery when needed) - Plan time and inventory buffering - Managing ripening process - Plan emergency repairs of vehicles and equipment	- Monitor supplier (freshness, product temperature) and transporter performances (thermograph) - Use tracking and tracing (supplier – retail's DC) - Rationalise product range - Perform aggregate forecasts - Keep short chain	- Performance monitoring systems for suppliers - Control forecast accuracy - Rationalise product range, only high-selling products - Proactive maintenance of cooling equipment and IT hardware - Use tracking and tracing - Keep short chain and carefully select suppliers
	- Plan delivery timing - Keep list of potential transport providers (various transportation means) and suppliers from different countries - Plan time and inventory buffering - Maintain fair relationships with suppliers (and intermediaries) - Make strategic alliances (as priority customer): Transport outsourcing,	- Control tolerances for freshness, product temperature, delivery times - Short planning period (two weeks), frequent deliveries (every day) - Use tracking and tracing (supplier – retail's DC) - Customise product at customer's request - Plan promotion to manage demand; - Keep occasional suppliers - Strategic alliances: supplier, 3PL (transport and distribution) - Request for vehicles equipped with GPS; Using TPS to optimise routes - Advance information on risks or disturbances from suppliers - Keep short chain	- Make strict requirements for suppliers - Define complaint procedures and penalties - Plan promotion - Short planning period (one week), frequent deliveries (3-7 times per week) - Use tracking and tracing - Financial incentive to suppliers during supply disturbances - Keep short chain - Carefully select suppliers
P3: *Development of disturbance prevention and risk management culture*	- Use experienced workers to handle ripening process and perform quality monitoring	- Train employees	- Use experienced workers - Train employees
	- Use standard working procedures to update contracts after disturbances (complaints, invoices)	- Closer cooperation with key suppliers when disturbance happens - Use experienced workers to increase warning capabilities - Use standard procedures for complaints and penalties	- Strict following company's procedures in regular situations as well as when disturbance occurs - Build awareness for crises situations

GFSI - Global Food Safety Initiative; IFS – International Food Standard; GMP – Good Manufacturing Practice; GHP – Good Hygiene Practice

Table 4. 6. Impact reductive redesign strategies: overview of three cases in relation to DMPs

Impact reductive principles	Case 1: bananas	Case 2: fresh meat	Case 3: fresh meat
R1: Redundancy	- Inventory of green bananas - Buffering in time - Use special ripening chambers	- Temporary storage area in outlets - Use both, conditioned vehicles and special meat containers	- Increase capacity of outlets
	- Buffering in time	- Use of cross-dock warehouse - Multiple suppliers in peak demand periods	- Multiple suppliers
R2: Flexibility	- Product form postponement - Use of standardised equipment and cross-functional teams	- Product form postponement - Product substitution (frozen program) - Multiple suppliers available, possible transhipment - Use of standardised cold-chain equipment and cross-functional teams	- Product substitution (frozen programme) - Possible transshipment
	- Product form postponement - Use different suppliers per period; intermediaries - Use promotion to reduce high stock level - Use multiple modes of transport	- Product form postponement - Multiple suppliers available, possible transhipment - Use promotion to sell overstock - High level of cooperation with key suppliers	- Spot purchase - Possible transhipment - Unsold products and products that do not comply with specifications are returned to supplier (Buy-back contracts)
R3: Information visibility	- Control of parameters relevant for ripening process and parameters of 3PL provider (distribution timing)	- Bar-code: tracking and tracing (supplier-distribution centre);	- Information available at retailer's request - Bar-code: tracking and tracing (supplier – retail outlet) - Temperature alarms in outlets
	- Reporting on delivery plan and stock levels in outlets - Reporting about disturbances using defined procedures and communication channels - Complaint and invoice to suppliers in the case of damaged delivery	- Complaint to suppliers (Penalty policy) - Bar-code: tracking and tracing (supplier-distribution centre); temperature alarms - Reporting on delivery plan and stock levels in outlets - Information sharing with key suppliers - Monitor key supplier's performances (freshness, product temperature) - Control of parameters of 3PL provider (timing, temperature), use of TMS, GPS	- Bar-code: tracking and tracing (supplier – retail outlet) - Complaint to suppliers (Penalty policy)
R4: Responsive-ness	- Response in the case of failure within 24hrs	- Fast offer of product substitution (frozen programme) - Fast replenishment in the case of damaged delivery (Buy-back contracts) - Response in the case of failure in 24hrs	- Fast offer of product substitution (frozen programme) - Unsold products and products out of specifications are replenished (Buy-back contracts)
	- Fast, additional delivery for outlets that run out of stock - Emergency supply from intermediaries	- Fast replenishment in the case of damaged delivery (Buy-back contracts) - Lead time management, cross-dock - Event driven planning (in transport) - Emergency supply – transshipment	- Emergency supply – trans-shipment - Lead time management, short term planning

4.3.3 Cross-case analysis

To deepen our understanding of the relationship between the four contextual factors and the application of different response principles, as well as to enhance the generalisability of our findings (Miles and Huberman, 1994), we performed a cross-case analysis. We start this section with some observations on the contextual factors themselves. Then we build on these observations to structure our analysis of the case study data. This interpretation of the data permits the observation of novel structural relationships between the application of DRM concepts and principles and the contextual factors themselves. These relationships are fully elaborated in the Findings section.

4.3.3.1 Adaptability of contextual factors

In the first step of the analysis of the case data, we considered the contextual factors from the point of view of SC actors. We observed a pertinent variation in the adaptability of the four factors. This variability ranges between factors that are easy to change within a short period of time and those that are hard to change even over a long period of time (see Table 4.7). From the table we can see that the SC business environment and products are harder to change for typical SC actors than the processes and SC network characteristics. For example, it is relatively easier to change a supplier or transporter than to influence customer preferences regarding particular food characteristics. This distinction is the key which indicates the scope for the use of DMPs and corresponding strategies, i.e. it defines the context for their use.

Table 4. 5. Adaptability of contextual factors

Contextual Factors		Ease of Change	Timescale of possible change affected	Examples Changing each Contextual Factor
D	SC Business Environment	Hard	Medium to Long term	-Marketing strategies to affect customer preferences for food -Lobbying for changes in regulatory environment
C	SC Network Characteristics	Relatively easy	Short to medium term	-Change Supplier -Shift production process to new location
B	SC Processes	Easy	Short term	-Buy a new machine -Change a delivery route
A	Products	Hard	Long term	-Genetic engineering to alter fresh food product characteristics -Breeding to alter fresh food product characteristics

The most pertinent relationships between the application of DMCs and DMPs and the contextual factors become clear once we observe that every application of a DMP in our case studies corresponds to *the interface between the characteristic of a factor that is hard to change and the characteristic of a factor that is easier to change*. For example, the market capacity risks for fresh food SCs (D1, see Table 4.4) clearly influence the choice of sourcing strategy (C4, see Table 4.4). This is due to the need for flexibility to reduce the impact of disturbances in the supply process (R2, see Table 4.6). The greater the number of relationships established with certified suppliers, the more flexible the SC is and, hence, the lower the impact of a failure of any one supplier. For example, a SC planning manager (Case 2) states: "The *company's regular supply strategy is based on supplying about 50% of the meat we buy from the supplier which is our strategic partner, and supplying somewhat less than 50% of the meat from another reliable supplier. Of course we always buy some meat from other suppliers as well, just to keep up contacts and maintain good relations in case of uncertain demands in the future…"*

Now we define these factors in the following way: the two contextual factors of food SCs that are hard to change even over the medium to long term, we refer to as ***hard*** *contextual factors*. The sub-characteristics of these factors shall be referred to as ***hard*** *contextual characteristics*. The two contextual factors of food SCs that are easier to change, even in the short to medium term, we refer to as ***soft*** *contextual factors*, for reasons that will be argued below. The sub-characteristics of these factors shall be referred to as ***soft*** *contextual characteristics*.

If we look at the detail of the application of DMPs to individual contextual characteristics, we can see that each principle is applied to the *interaction* of a hard contextual characteristic (i.e. an environment or product characteristic) and a more adaptable i.e. soft contextual characteristic (i.e. a network or process characteristic), which lead us to the following *preliminary finding*:

The hard characteristics impose requirements to the application of DMPs on the SC scenario. The SCs respond to these requirements during disturbances by adapting the soft characteristics in line with DMPs.

This preliminary finding states that the DMP applied in a SC scenario depends on how the soft characteristics can be adapted to the hard characteristics. More specifically, the DMP used (P1-P3, Table 4.5; R1-R4, Table 4.6), depends on how the soft characteristic (B1-B8, C1-C8, Table 4.1), can be adapted to the particular hard characteristic (A1-A5, D1-D3, Table 4.1).

As will be argued in the next section, we find that the DMP which is applied to interactions between one of the hard contextual factors and either the SC network or process depends on the particular combination of contextual factors examined. The support for this interpretation is the meaningful relationship between the DMPs applied in practice and the particular contextual factors involved, which is discussed in detail in the findings section.

4.3.3.2 Guide to Data analysis

We begin with a note on the descriptions that we will use in the text to explain the two Tables (4.8 and 4.9), where the results of the case study analysis are presented.

Firstly, we discuss the organisation of the two tables, one of which concerns preventive DMPs and the other impact reductive DMPs. The soft contextual characteristics are organised by column. Each soft contextual characteristic is further sub-divided into three sub-columns denoting the three case studies (1 to 3). The hard contextual characteristics are organised in rows. Each hard contextual characteristic is further sub-divided into sub-rows denoting each of the relevant DMPs (P1 to P3 or R1 to R4).

A *field* is the conjunction of a hard contextual characteristic (A1 to A5, D1 to D3), a particular DRM principle (P1 to P3, for Table 4.5; R1 to R4 for Table 4.6), and a soft contextual characteristic (B1-B8, Table 4.3; C1-C8, Table 4.4). The field that corresponds to the conjunction of the *hard contextual characteristic* A4, DMP P3, and the *soft contextual characteristic* B5, shall be denoted [A4-P3]^B5 in the text.

A *sub-field* is one of the three case studies (1, 2 or 3) within a *field*. The sub-field for case study 2 within [A4-P3]^B5, is denoted [A4-P3]^[B5-2]. A *sub-field* is marked whenever analysis of the corresponding case study has shown the relevant DMP is applied to adapt the *soft* characteristic to the requirement imposed by the *hard* characteristic.

For example, the preventive DMP "*Assurance and reliability systems*" (P1) is applied to the *soft* characteristic "*process resources*" (B1) in order to adapt to the requirement imposed by the *hard* characteristic "*shelf life*" (A1). This is represented in Table 4.8, by the **X**s in each of the three sub-fields of the [A2-P1]^B1 field, with each sub-field corresponding to a case study (1 to 3). The tables also show the SC scenario element to which each *soft* characteristic belongs, and whether it is a specific *process* or part of the SC *network*. This is read by referring to the fields above the soft characteristics codes. So, for the example given in the previous paragraph, we see that B1 corresponds to the process's managed system.

To arrive at our findings we interpreted Tables 4.8 and 4.9 using the following rules:

1. If a DMP concept is applied more than once to a soft contextual characteristic (B1-B8, C1-C8) for either hard contextual factor (product or environment), there is a non-negligible relationship between them. Such areas are shaded grey in Tables 4.8 and 4.9.
2. Whenever three **X**s appear in each *sub-field* within a *field*, this means that the DMP has been applied in each of three case studies, for the corresponding intrinsic and soft contextual characteristics. *This means that the DMP applies to fresh food chains across the breadth of scenarios represented by our case studies*.
3. Whenever two **Y**s appear in the second and third *sub-fields* within a *field*, this means that the corresponding DMP has been applied in both local meat-assortment SCs studied (Cases 2 and 3), i.e. similarities in one environmental characteristic and in product type.
4. Whenever two **Z**s appear in the first and second *sub-fields* within a *field*, this means that the corresponding DMP has been applied in both SCs which are designed to allow product customisation during buffering (Cases 1 and 2), i.e. similarities in process characteristics.
5. **O** denotes the application of a DMP in only one case *sub-field* within a *field*.

4.4 Main findings

By analysing Tables 4.8 and 4.9, our first observation is that both DMCs are used in fresh food SCs, as found in the literature. However, there is a difference in how and why they are used. Hard contextual characteristics play a key role in the application of DMCs, as highlighted in the preliminary findings in the previous section.

Based on the rules we defined in Section 4.3.3.2, we explain our findings regarding the application of DMPs (Tables 4.8 and 4.9). Both hard contextual factors strongly influence the choice of DMPs. The application of DMPs is constrained by the capacity of the soft factors (*processes* and *SC networks*) to respond to the requirements of the hard factors (*products* and the *business environment*).

Table 4. 8. Use of Preventive DMPs in relation to Contextual factors and their characteristics

Contextual factors			Process																							
			Managed system						Managing system						Information system						Organizational structure					
			B1			B2			B3			B4			B5			B6			B7			B8		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Product	A1	P1	X	X	X										X	X	X	Z	Z							
		P2		Y	Y	O				Y	Y					Y	Y		O						O	
		P3																								
	A2	P1	X	X	X										X	X	X	Z	Z							
		P2		Y	Y					O						Y	Y		O						O	
		P3	O			O									O			O						O		
	A3	P1																X	X	X						
		P2	O												O									O		
		P3	O			O									O			O						O		
	A4	P1																								O
		P2				O							Y	Y								Y	Y		O	
		P3		Y	Y									O		Y	Y		O						O	
	A5	P1				Z	Z																			O
		P2	O			O									O									Z	Z	
		P3	Z	Z		O									Z	Z			O					Z	Z	
Environment	D1	P1																								
		P2										O														
		P3																								
	D2	P1																								
		P2				O			X	X	X														O	
		P3																								
	D3	P1																								
		P2																								
		P3																								

Contextual factors			Network																							
			Managed system						Managing system						Information system						Organizational structure					
			C1			C2			C3			C4			C5			C6			C7			C8		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Product	A1	P1																								
		P2				X	X	X														O		O		
		P3																								
	A2	P1																								
		P2															O									
		P3																								
	A3	P1																								
		P2																								
		P3																								
	A4	P1																								
		P2															O									
		P3																								
	A5	P1																								
		P2																								
		P3																								
Environment	D1	P1							O			O												O		
		P2			O	X	X	X			O		O			O					X	X	X	Z	Z	
		P3												O								O				
	D2	P1																								
		P2	Z	Z		O						Z	Z							O		O			O	
		P3										O														
	D3	P1							O															X	X	X
		P2				X	X	X		O						Y	Y		Y	Y		Y	Y	O		
		P3										O		O	Z	Z							O	O		

Legend: The table shows the applications (denoted **X**, **Y**, **Z** or **O**) of Preventive DMP principles (P1 to P3, see Table 4.2), to every possible combination of a *Hard* contextual characteristic (see (A1 to A5), (D1 to D3) in Table 4.1) and a *Soft* contextual characteristics (see (B1 to B8), (C1 to C8) in Table 4.1), for each case study (1 to 3). The precise meaning of the symbols in this table is described in section 4.3.3.2.

Table 4. 9. Use of Impact Reductive DMPs in relation to Contextual factors and their characteristics

Contextual factors			Process																							
			Managed system						Managing system						Information system						Organizational structure					
			B1			B2			B3			B4			B5			B6			B7			B8		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Product	A1	R1		O						O																
		R2																								
		R3			O																					
		R4																								
	A2	R1		O		O																				
		R2																								
		R3			O																					
		R4	Z	Z									Y	Y												
	A3	R1		O		O																				
		R2																								
		R3	O						O																	
		R4	Z	Z																						
	A4	R1				X	X	X																O		
		R2	Z	Z									Y	Y				O							O	
		R3		Y	Y														Y	Y					Y	Y
		R4						O											O						O	
	A5	R1	Z	Z		Z	Z																	Z	Z	
		R2	Z	Z		O							O					O						Z	Z	
		R3		O															O						O	
		R4																	O						O	
Environment	D1	R1																								
		R2																								
		R3																								
		R4																								
	D2	R1																								
		R2				Z	Z																			
		R3				O												O								
		R4				O																				
	D3	R1																								
		R2												O												
		R3		O															O							
		R4																								

Contextual factors			Network																							
			Managed system						Managing system						Information system						Organizational structure					
			C1			C2			C3			C4			C5			C6			C7			C8		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Product	A1	R1																								
		R2																								
		R3																								
		R4																								
	A2	R1				O																				
		R2																								
		R3																								
		R4																								
	A3	R1																								
		R2																								
		R3																								
		R4																								
	A4	R1						O																		
		R2					Y	Y					O													
		R3															O									
		R4																								
	A5	R1				O																				
		R2																								
		R3															O									
		R4																								
Environment	D1	R1			O									O				O								
		R2				Z	Z		O			X	X	X		O					O			O		
		R3																								
		R4																								
	D2	R1		O			Y	Y					O									O				
		R2	O			X	X	X						O												
		R3													O									O		
		R4				O									O									O		
	D3	R1																								
		R2																		O		O				
		R3							O						X	X	X		Y	Y	Z	Z				
		R4				X	X	X											Y	Y		Y	Y	X	X	X

Legend: The table shows the applications (denoted **X**, **Y**, **Z** or **O**) of Impact reductive DMP principles (R1 to R4, see Table 4.2), to every possible combination of a *Hard* contextual characteristics (see (A1 to A5), (D1 to D3) in Table 4.1) and a *Soft* contextual characteristics (see (B1 to B8), (C1 to C8) in Table 4.1), for each case study (1 to 3).
The precise meaning of the symbols in this table is described in section 4.3.3.2.

4.4.1 Application of Preventive Disturbance Management Principles

To arrive at the first proposition regarding the preventive DMC we interpreted Table 4.8 using the first rule in section 4.3.3.2.

In the top left quadrant each symbol represents the application of a preventive DMP to modify a process according to the requirements imposed by a hard, inherent characteristic of a (fresh food) product. For example, in Table 4.8 all three types of preventive DMPs are used to modify processes in every element of SC scenario according to the requirements imposed by sensory properties of fresh food products (A2). However, the same does not apply for SC network. The *prevalence* of such symbols in the product/process quadrant, and the relative absence of symbols in the product/network quadrant lead to the following proposition:

Π.1 In order to cope with the requirements imposed by fresh food products, preventive DMPs are applied more often to processes than to the SC network to maintain robust performances.

A notable exception to proposition 1 is the field: [A1-P2]^C2, which shows that the DMP "*Proactive control, analysis and monitoring*" (P2) is applied in every case. The constraint on the operation of the SC due to the hard product characteristic of a short "*shelf life*" (A1) is compensated for by applying the P2 on the soft network characteristic "*SC network structure*" (C2). In Case 1, this corresponds to extending the SC to include a special warehouse in order to manage the ripening process. In Case 2, this corresponds to building the cross-docking DC to speed up product flow. In Case 3 this means adjusting the SC network to directly deliver final products from suppliers to outlets.

In the bottom right quadrant each symbol represents the application of a preventive DMP to modify the SC network to the requirements imposed by the hard, external characteristic of the SC business environment. For example, in Table 4.8 all three types of preventive DMPs are used to modify the SC network in every element of the SC scenario according to the requirements imposed by stakeholders (retail systems) (D3). However, the same does not apply for processes. The *prevalence* of such symbols in the SC business environment/network quadrant, and the relative absence of symbols in the SC business environment/process quadrant lead to the proposition:

Π.2 In order to cope with the requirements imposed by the SC business environment preventive DMPs are applied more often to the SC networks than to the processes to maintain robust performances.

A notable exception to proposition Π.2 is the field: [D2-P2]^B3, which shows that the DMP "*Proactive control, analysis and monitoring*" P2 is applied in every case. The constraint on the operation of the SC due to the hard business environment characteristic of "*uncertainty in both supply and demand*" (D2) is compensated for, in each case, by applying the preventive DRM principle P2 to the soft process characteristic "*timing constraints*" (B3). This corresponds to use of frequent deliveries to retail outlets in order to make the end of the chain more responsive to the uncertain demand. This need for responsiveness highlights a potential weakness in the SCs, as supply is also uncertain. Hence, the application of numerous strategies in each of the SCs to reduce the impact of mismatches of supply and demand, especially failures to meet demand.

To analyse the application of a particular DMP, let's use the following example: a short shelf life (A1) for fresh products is a *hard* characteristic that is difficult to change. A soft characteristic of the SC scenario that adapts to this unavoidable constraint imposed by a hard characteristic of the product is "*specialised resources for product transformation and storing*" (B1). Concretely, this means the cooling equipment that is required to be used in order to apply the preventive DMP "*assurance and reliability systems*" (P1), which prevents the fresh products from decaying. Another *soft* characteristic that adapts to the constraints imposed by this *hard* characteristic is the "*information systems that support product quality preservation*" (B5), such as the measuring and recording devices, again required to implement P1, which monitor the temperature at which the product is stored. This example is symptomatic of the prevalence of applications of the preventive DMP "*assurance and reliability systems*" (P1) to the soft contextual factor process, to cope with the unavoidable constraints imposed by the inherent characteristics of products. This leads to the proposition:

Π.3 In order to cope with the requirements imposed by fresh food products, the main preventive DMP applied to processes to maintain robust performances is "assurance and reliability systems".

Preventive DMPs in fresh food SCs are frequently applied to the managed system (especially B1) and the information system (B5 and B6) of processes, as can readily be seen in Table 4.8 for the use of "*assurance and reliability systems*" (P1) in all three cases.

The data indicates that fresh food SCs frequently use "assurance and reliability systems" (P1) as a DMP. However, this DMP is mainly used for processes, and to a much lesser extent for the SC network. However, the data shows that the use of P1 is initiated by stakeholders (retailers in our cases), who request the implementation of certain food standards and protocols along the chain. The preventive DMP "*disturbance prevention and risk management culture*" (P3) is rarely applied in the SCs studied, as evidenced by Table 4.8. Its application is localised to either the part of the chain that is under the direct control of the retailers [D3-P3]^[SC Network], or those that require skilled workers [A4-P3]^[process], and [A5-P3]^[process].

The following example introduces the next proposition. The number of qualified and certified suppliers available on the market (D1) influences the organisational structure of the SC network with respect to the collaboration level during disturbances (C7). Our case analysis shows that companies are using preventive DMP "Proactive control, analysis and monitoring" (P2) in the following way: In Case 1 the retailer keeps transactional relations with its suppliers and keeps a list of additional potential suppliers on other markets; In Case 2 the retailer cultivates strategic partnerships with two main suppliers and keeps occasional suppliers as well; In Case 3 the retailer plans financial incentives for suppliers in case of disturbances to help correct the system.

Π.4 In order to cope with the requirements imposed by the SC business environment, the main preventive DMP applied to SC networks to maintain robust performances is "proactive control, analysis and monitoring".

We now present propositions regarding the relationships between contextual factors through the use of preventive DMPs on the Figure 4.2.

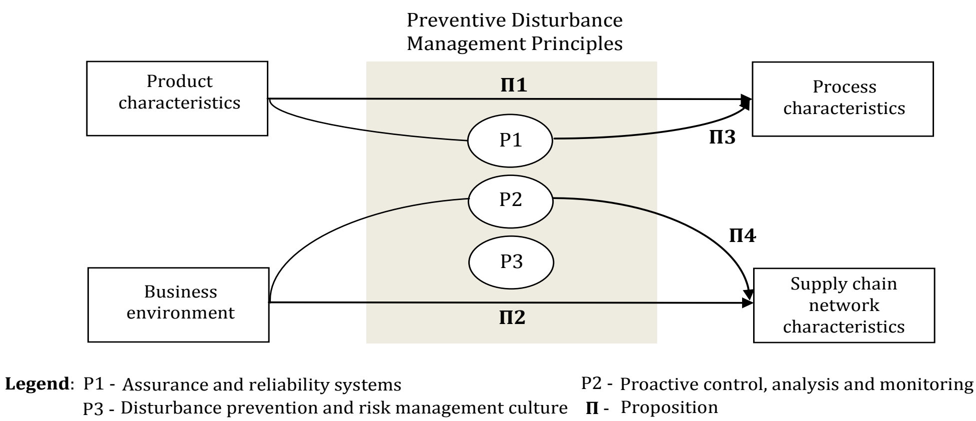

Figure 4. 2. Conceptual model: Relationships between contextual factors through the use of preventive DMPs

4.4.2 Application of Impact Reductive Disturbance Management Principles

To arrive at the first proposition regarding the impact reductive DMC we interpreted Table 4.9 using the first rule in section 4.3.3.2.

In the top left quadrant each symbol represents the application of an impact reductive DMP to modify a process according to the requirements imposed by a hard, inherent characteristic of a (fresh food) product. For example, in Table 4.9 all four types of impact reductive DMPs are used to modify processes in every element of the SC scenario according to requirements imposed by fresh food product assortment (A4). The relative prevalence of such symbols in the product/process quadrant, and the relative absence of symbols in the product/network quadrant lead directly to the proposition:

Π.5 In order to cope with the requirements imposed by fresh food products, impact reductive DMPs are applied more often to processes than to the SC network to maintain robust performances.

However, there is only one instance of an impact reductive DMP "*Redundancy*" (R1) which applies in all three case studies in the Product/Process quadrant. Moreover, analysis of this quadrant using rules 2 to 5 (section 4.3.3.2) leads the following supplementary finding to proposition Π.5: The case findings show that the choice of the appropriate impact reductive DMP is dependent on the product characteristics.

The particular types of SC for which we see this dependence are: SCs that are designed to allow product customisation during buffering, and local SCs with product assortment. The specific evidence that support this supplement to proposition Π.5 is derived from Table 4.9:

a) The impact reductive DMP "redundancy" (R1) is more likely to be applied to soft contextual characteristics of the managed system and the organisational structure to cope with the requirements imposed by the hard product characteristic "product customisation" (A5). This is especially true for the SCs designed to allow product customization during buffering (Cases 1, 2), as can be seen from the prevalence of pairs of **Z** symbols in the product/process quadrant.

b) The impact reductive DMPs "flexibility" (R2) is more likely to be applied to elements of the managed systems, and to the organisational structure to the certain extent, to cope with the requirements imposed by the hard product characteristics "product assortment" (A4) and "product customization" (A5). This can be seen from the appearance of pairs of **Y** and **Z** symbols in the product/process quadrant (columns that correspond to process's managed system and organizational structure).

c) The impact reductive DMP "information visibility" (R3) is likely to be applied to all elements of the SC scenario regarding processes to cope with the requirements imposed by the hard product characteristics. However, application of this DMP is a) specific for local SCs with product assortment, as can be seen from the prevalence of pairs of Y symbols in the R3 rows in product/process quadrant and b) case specific, as can be seen from the prevalence of O symbol in rows R3 in the product/process quadrant. For example, information visibility regarding weight loss (A3) is especially present in Case 1, regarding product customizations (A5) in Case 2 and regarding shelf life (A1) and sensory properties (A2) in Case 3.

d) The impact reductive DMPs "responsiveness" (R4) is more likely to be applied to elements of the managed and managing systems to cope with the requirements imposed by the hard product characteristics "sensory properties" (A2), "weight loss" (A3), ". This can be seen from the appearance of pairs of Y and Z symbols in the product/process quadrant (columns that correspond to process's managed and managing system). However, prevalence of O symbol in rows R4 that correspond to Case 2 for instance (field [A4-R4]^B6,B8 and field [A5-R4]^B6,B8) in the product/process quadrant indicates case specific requirements imposed by meat-assortment (A4) and customisation options (A5) to information system for logistic support (B6) and customization activities (B8).

This more detailed analysis indicates a strong influence of product characteristics on the impact reductive principles used.

A notable exception to proposition Π.5 is the field: [A4-R2]^C2, which shows that the impact reductive DMP "*Flexibility*" (R2) is applied in both local meat-assortment chains. Constraints on the operation of the SC due to the hard product characteristic "*assortment*" (A4) is compensated for, in cases 2 and 3, by the application of the R2 to the soft network characteristic "SC network structure" (C2). This corresponds to the possibility of trans-shipment in both cases due to both the particular product assortments and formats of outlets (hypermarkets).

The following example introduces the next proposition. The number of qualified and certified suppliers available on the market (D1) influences the managing system of the SC network with respect to the sourcing strategy applied during disturbances (C4). Our case analysis shows that, during disturbances in supply companies use the impact reductive DMP "*flexibility*" (R2) in the following way: switching to a different supplier in another market (Case 1), purchasing from several occasional suppliers with whom established relationships are constantly maintained (Case 2), and offering a higher price to ensure supply (Case 3). In the bottom right quadrant of Table 4.9 each symbol represents the application of an impact reductive DMP to modify the SC network according to the requirements imposed by the hard characteristic of the SC business environment. For example, in Table 4.9 all four types of impact reductive DMPs are used to modify SC network in every element of SC scenario according to requirements imposed by market characteristics in Serbia (D2). The *prevalence* of such symbols in the SC business environment/network quadrant, and the relative absence of symbols in the SC business environment/process quadrant lead directly to the proposition:

Π.6 In order to cope with the requirements imposed by the SC business environment, impact reductive DMPs are applied more often to SC networks than to processes to maintain robust performances.

It is worthwhile noting that the actual application of R2 as an impact reductive strategy is enabled by the use of P2 (*proactive control, analysis and monitoring*) to establish a particular type of relationship with suppliers.

A notable exception to proposition Π.6 is the field: [D2-R2]^B2, which shows that the DMP “*flexibility*” (R2) is applied in both SCs designed to allow product customisation during buffering. The requirements to the SC due to the hard SC business environment characteristic of uncertainty in both supply and demand (D2-market characteristics) is compensated, in cases 1 and 2, by applying the R2 to the soft process characteristic “*inventory*” (B2). This corresponds to the inventory of raw materials (green bananas and meat parts, Cases 1 and 2 respectively). A further exception is the two fields: [D2-R3, R4]^B2, which show that the DMPs “*Information visibility*” (R3) and “*Responsiveness*” (R4) are applied in Case 1. The requirements to this SC are due to the hard SC business environment characteristic of uncertainty in both supply and demand (D2-market characteristics). These requirements impose adaptation, in Case 1, by applying the R3 and R4 to the soft process characteristic “*inventory*” (B2). Concretely, this corresponds once more to the inventory of raw materials (green bananas) by having information visibility on inventory status (R3) and being prepared for emergency deliveries to outlets with unforeseen demand (R4).

To analyse the application of particular DMPs, let’s use following example: the “*severity of stakeholders’ requirements*” (D3) is a hard characteristic of the SC environment. A soft characteristic of the SC scenario that adapts to this is the managed system (C2-network structure) and the organisational structure (C8-strategic partnerships) by use of DMP “*responsiveness*” (R4). This means that both the network structure and strategic partnerships are shaped with consideration of stakeholders requirements (retailers). Regarding the network structure: in Case 1, the retailer determines the length of the chain by choosing its foreign suppliers and transport options; in Case 2, the retailer shapes the network structure by a) introducing a cross-dock cold warehouse to speed up product flows and transshipment between hypermarkets; in Case 3, the retailer shapes the network structure by enabling transshipment between hypermarkets. Regarding strategic partnerships: in Case 1 and 2, the retailers maintain closely controlled relationships with their 3PL providers due to the tight tolerance windows for deliveries, while in Case 3 the retailer imposes a high penalty on suppliers for slow responses to changes in demand or supply.

The application of R2 results from two hard characteristics of the SC environment: "*market capacity risks*" (D1) and "*market characteristics*" (D2). A soft characteristic of the SC scenario that adapts to D1 is within the managing system (C4-sourcing strategy), as explained in the example given for proposition Π6. A soft characteristic of the SC scenario that adapts to D2 is part of the managed system (C2-network structure). Regarding the network structure, due to the uncertainty in both supply and demand in Case 1, the retailers increase flexibility in the network by having back-up suppliers and by using multiple modes of transport; in Cases 2 and 3 the retailer shapes the network structure by enabling transshipment between hypermarkets to cover inventory shortages.

These examples show applications of the impact reductive DMPs R2 and R4, to cope with the requirements imposed by the hard characteristics of the SC business environment. This leads to the proposition:

Π.7 In order to cope with the requirements imposed by the SC business environment, the main DMPs applied to SC networks to maintain robust performances are "flexibility" and "responsiveness".

As described directly after the statement of proposition Π.5, in fresh food SCs we analysed there is only one instance of an impact reductive DMP "Redundancy" (*R1*) which is applied in all three case studies in the Product/Process quadrant. This limited application of the same DMPs across all three chains is most noticeable for the soft characteristics: high perishability (A1) and sensitivity of fresh food products (A2), which increase the complexity of inventory management. This complexity requires specialised resources (B1) and limited inventory levels (B2). Moreover, the limited application of the DMP "*information visibility*" (R3) results from requirements imposed by a hard characteristic of the SC environment "*Severity of stakeholder's requirements*" (D3). In the cases analysed, requirements for tracking and tracing are imposed only by retailers and they are limited to the part of the SC under their control. This leads to the proposition:

Π.8 In order to cope with the requirements imposed by both, fresh food characteristics and the SC business environment, the DMPs "redundancy" and "information visibility" are those least applied to processes and SC networks to maintain robust performances.

In Figure 4.3 we present propositions regarding relationships between contextual factors through the use of impact reductive DMPs.

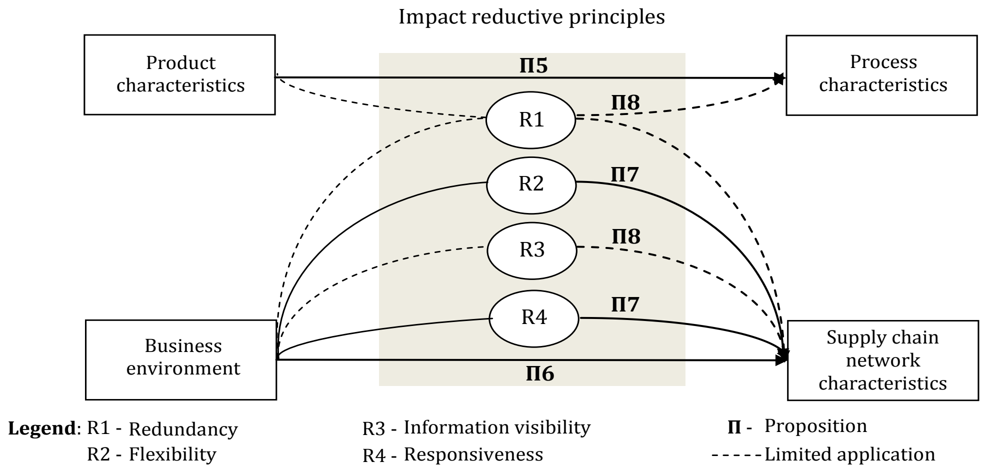

Figure 4. 3. Conceptual model: Relationships between contextual factors through use of impact reductive DMPs

4.5 Conclusion and further research directions

Case study analysis confirms the theoretical indications that contextual factors influence the use of DMPs to manage disturbances. Our findings, based on three explorative case studies, are directly relevant to the research question: What is the relationship between the (characteristics of) contextual factors of food SCs and the use of DMPs?

We highlight that the importance of contextual factors lies in the fact that these contextual factors may create vulnerability sources, or influence control actions and therefore influence disturbance management. Contextual characteristics of the product and business environment (hard contextual characteristics) represent potential vulnerability sources and as such influence the selection of DMPs. Process and SC characteristics (soft contextual characteristics) represent the elements of the SC scenario that are affected by the use of the DMPs.

Our findings show the merit of the insight that in SCs, as elsewhere, the things that actors cannot change, determines how they act upon those things that they can change. This principle can be observed in our case studies as the SC actors alter the soft contextual characteristics of the SC network due to requirements derived from the hard contextual characteristics of fresh food products and the business environment considered in the study (Serbian business environment). Notably, there is a research opportunity to investigate the relevant hard and soft characteristics for non-perishable food products, as well as for other industries and markets.

Hard characteristics (of products and markets) are specific to every SC, and they are their essential property: What is produced? And why? Product and SC environment characteristics are hard characteristics of fresh food SCs and they shape vulnerability sources, i.e. the specific weaknesses of these chains. As such they influence the selection of DMCs and the corresponding DMPs. Soft characteristics on the other hand are influenced by DMPs and their importance lies in the opportunities they provide for the application of the DMPs. For example, to preserve product quality, the stability of product characteristics must be maintained, which implies the use of DMPs and particular redesign strategies - a strict freshness criteria for certain food products limits the supply base by posing very strict lead-times, e.g. only local suppliers could be considered.

As suggested in the SCM literature (Lewis, 2003; Kleindorfer and Saad, 2005), we confirmed that both DMCs, preventive and impact reductive are used in fresh food SCs. However, the DMPs that belong to these concepts are used for processes or SC networks for different elements of the SC scenarios (managed-, managing-, and information- systems, and the organisational structures), with various frequencies.

The most significant finding is that both preventive and impact reductive DMPs are more likely to be applied either to processes to cope with the requirements due to hard fresh food product characteristics or to SC network characteristics to cope with requirements arising from business environment characteristics. However, another important finding is that the impact reductive principles applied are very dependent on product characteristics, (e.g. what are assortment and customization options). Another research opportunity would be to investigate whether the main finding holds for non-perishable products, other industries as well as if chains are analysed from supplier's perspective. Furthermore, the very rare application of any DMPs to return flows, is indicative of the power of the large retailers considered in these case studies to transfer risks to other SC actors. Indeed, the only instance of any DMPs principle being applied to return flows is the use of tracking and tracing to monitor the responsibilities of the other actors.

Focusing on the use of preventive DMPs, our research findings indicate that fresh food SCs use assurance and reliability systems (P1) and proactive control, analysis and monitoring (P2) very often. However, P1 is mainly used at the process level, and to a much lesser extent at the SC level. This is in line with the finding that risk management culture (P3) is poorly developed in the SCs studied. The main reason for the frequent application of principle (P1) is the rapid development of assurance and reliability systems in the food industry (cf. Luning et al., 2002; Matopoulos et al., 2007), and also a growing awareness about SC vulnerability generally (Wagner, and Neshat 2010). The data shows that the use of assurance and reliability systems is initiated by stakeholders (retailers in our cases), who request the implementation of certain food standards and protocols along parts of the chain under their immediate control. This is in line with the finding that DMP "*disturbance prevention and risk management culture*" (P3) is poorly developed in the SCs, which reflects the specific SC business environment in Serbia with regard to fresh food SC. There is a question as to whether the patterns of use of these DMPs (P1 and P3) would be the same for small and medium enterprises (SMEs). On the other hand, P2 is mostly used to cope with the hard constraints that come from the SC environment and they are applied in SC networks. The main reason for the frequent application of principle (P2) in SC networks is associated with avoiding vulnerability sources due to the inability of companies that are doing business in Serbia to control them.

In line with Lewis (2003), our case analysis shows that an over-reliance on prevention and mitigation control may decrease SC responsiveness. We observed in Case 1 that due to sourcing bananas from international suppliers, the supply part of the chain is characterised by standardised assurance and reliability systems, international trade protocols and the business practice of local suppliers at the beginning of the chain. Therefore, when disturbances affect incoming shipments, the responsiveness of the supply part of the chain is dramatically low. Nonetheless, in Case 1 hard product characteristics enable a sufficient use of impact reductive DMPs (redundancy based on product customisation during buffering, flexibility to find alternative suppliers that comply with the stakeholder's requirements and sufficient information visibility in the retail system) that compensate for the risks of low responsiveness in the supply part of the chain. It remains an open question what are the typical DMPs that might compensate for poorly responsive supply side of the chain in the case of non-perishable food products or SCs in other industries, without creating high inventory costs.

Focusing on the use of impact reductive DMPs, our research findings indicate that they are more likely applied to cope with the constraints due to hard business environment characteristics. This is in line with Vlajic et al. (2012a) where it is stated that impact reductive DMPs are used more when the SC is exposed to the less controllable sources of vulnerability.

Appendix 4.1

In this appendix we enclose summaries of our transcripts structured in line with presented contextual characteristics in section 4.2.1.

Product characteristics

In the selected cases, we investigated perishability-related quality attributes as well as a Stock Keeping Unit (SKU) format and customisation opportunities in the retail system and in the supply part of the chain. All three products are risky, perishable products from a retailer's viewpoint: they have a short shelf life and sensory properties that easily change in unfavourable situations. The selected products also have some joint characteristics that have to be considered in SC design and planning as they are, e.g. unavoidable weight loss. Additionally, selected fresh food products have different characteristics from the perspective of consumer packaging format and customisation opportunities in retail outlets. The products are unpacked (Case 1: bananas), packed upon request (Case 2: fresh meat) or pre-packed (Case 3: fresh meat). From the perspective of customisation, products are sold with different ripening levels (Case 1: bananas), size and structure (Case 2: fresh meat) or in the same format as they are delivered from the supplier (Case 3: fresh meat).

Process characteristics

In line with the identified contextual process characteristics (see Section 4.2.1.2), we present our findings from the selected case studies.

In terms of the managed system at the process level, in retail outlets fresh food products are kept in special temperature-controlled zones (B1, Case 2, 3) or separate product-defined locations (B1, Case 1). For the realisation of production and logistic activities, specialised production (Case 1) and processing locations, as well as equipment are needed (Case 2, 3). When an atmosphere-controlled environment is needed, specific temperature and humidity parameters have to be maintained, products have to be stored in separate chambers, and hygienic requirements have to be fulfilled. For example, fresh meat (halves, carcasses) has to be transported in special refrigerated trucks, equipped with devices for temperature regulation and monitoring (Case 2, 3), while green bananas have to be transported in refrigerated containers (Case 1). In Case 1 and 2 minimal inventories in a particular format are kept, and Case 3 has a zero inventory due to JIT supply.

In terms of the managing system, *timing constraints* are relevant for all three cases, but they have a slightly different context. In Case 1, timing constraints are conditioned by the organisation of incoming transport, while in Cases 2 and 3 timing constraints result from strict product quality requirements (retailers demand very fresh meat products). Production throughput time is long in all cases, but there is a difference in the duration of order lead time. In Case 1 order lead time is usually a couple of weeks or more. In Cases 2 and 3 the required order lead time is very short. *Order characteristics* are product- and supplier-dependent. Due to a long and complex transport chain, and perishability of the product, volume requirements in Case 1 are not driven primarily by agreements with the supplier, but mostly by the requirements of the transport chain (capacity of special containers, transport and handling prices). In Cases 2 and 3 the risk of stock-outs or write-offs in outlets results from ordering rules: retailers order fixed quantities, and in Case 2 the retailer even has to purchase whole meat parts and halves (production SKUs).

The information system at the process level is based on controllers and sensors used to set and control temperature, humidity and ventilation parameters in facilities, chambers and transport compartments. In order to provide high-level customer service in fresh food chains, software for transport and warehouse management is typically used as a separate application (Case 1, 2) or software for Supplier Relationship Management is used within Enterprise Resource Planning (Case 3).

The organisational structure at the process level depends on product category and assortment management in retail system. Various processing steps are performed not only in the supply part of the chain, but also in retail outlets (Case 1, 2). In these cases, processing steps are supported by a safety inventory and buffers in retail systems. Moreover, depending on the retailer inventory policy (inventory strategy, type of product ordered), retailers can influence the production programme at the processor/supplier (Case 3). In all three cases return flows are the responsibility of the retailers (Case 1) or suppliers (Case 2, 3), while in Case 2 the supplier is responsible for handling by-products as well.

Supply chain characteristics

In line with the identified contextual SC network characteristics (see Section 4.2.1.3), we present our findings from the selected case studies.

In the managed system of fresh food chains, supplier capacity might be limited by technical characteristics of the machinery (Case 2, 3), or dependent on weather conditions (Case 1). *SC structure* varies from case to case depending on the number of actors involved and their ability and capacity to perform the required processing steps. Case 1 has a long SC because of international suppliers, a multi-mode transport chain and necessary administrative actors (e.g. customs and quality check-points). Case 2 and Case 3 are short local chains. Case 1 and 2 have a large retail system that consists of small, medium and large outlets, while Case 3 has a smaller retail system that consists of only large outlets.

We consider sourcing-related activities as the most important for fresh foods within the managing system at the process level. We found the use of different sourcing strategies in all three cases: in Case 1 the retailer has a preferred supplier, in Case 2 the retailer practises dual sourcing in normal conditions (50% of material is supplied from the own supplier, and another 50% from other suppliers) and in Case 3 the retailer keeps multiple suppliers as a regular strategy. The ensured product quality is usually associated with certification of suppliers (Case 2, 3), but in some cases product quality is defined in agreement and contract between retailer and supplier (Case 1).

Regarding information systems, SC managers identified the type and frequency of information exchange as well as triggers for response action as important elements of the *warning capability* of the company. In Case 1, information exchange is limited and standardised by protocols. In Case 2, information exchange is also limited, but suppliers inform retailer about disturbance or the risk of it. In Case 3, information exchange is richer, but it happens only at the request of the retailer. Triggers for responsive action in all three cases are in line with the severity of the stakeholders' requirements (see Section 4.3.2.1.d).

At the network level, organisational structure in food SCs mostly depends on power distribution: power can be in the hands of the supplier (Case 1: international SC, foreign suppliers are in a transactional relationship with retailers), it can be balanced between retailer and supplier (Case 2: both retailer and supplier are part of a large company) and it can be in the hands of the retailer (suppliers compete on the market, Case 3). From the perspective of strategic partnerships, the following types of *transport and distribution strategy* are found: in Case 1, incoming transport is arranged by a Third Party Logistic (3PL) provider, and distribution to retail outlets is performed by a local 3PL who gives priority of service to the retailer. In Case 2, suppliers deliver meat to cross-docking DC, and from there distribution is organised in the same way as in Case 1. In Case 3 distribution is also performed by the supplier.

Supply chain business environment characteristics (supply market)

Market capacity risk is present in the selected cases due to: geographically dedicated supply base (Case 1: banana suppliers are geographically limited to Central and South America, Africa and Asia); lead time restrictions (Case 2, 3 – freshness of the product requires short lead time, thus limiting the supply base to local suppliers), and limited availability of qualified and certified suppliers.

All three cases share similar characteristics of *supply market*: products are available throughout the year, but there is uncertainty regarding quality and quantity, as well as a slight seasonal impact. *Demand market* characteristics are predictable to a certain extent, but seasonal effects are present.

The *severity of requirements* regarding KPI values is defined by the focal company, i.e. the retail system. We measured the severity of requirements defined by retail system regarding delays, quality and quantity deviations. Tolerances are case- and KPI-dependent: Case 3 has strict tolerances, while Cases 1, 2 have slightly more relaxed tolerances (except for the delivery window to DC in Case 1)

5. Using vulnerability performance indicators to attain food supply chain robustness

This chapter is based on the published journal article:

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Production Planning and Control, The Management of Operations,
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In this chapter we answer Research Question **4**:
How to systematically assess the impact of disturbances in SC processes on the robustness of (food) SC performances?

Abstract

High effectiveness and leanness of modern supply chains (SCs) increase their vulnerability, i.e. susceptibility to disturbances reflected in non-robust SC performances. Both the SC management literature and SC professionals indicate the need for the development of SC vulnerability assessment tools. In this article, a new method for vulnerability assessment, the VULA method, is presented. The VULA method helps to identify how much a company would underperform on a specific Key Performance Indicator in the case of a disturbance, how often this would happen and how long it would last. It ultimately informs the decision about whether process redesign is appropriate and what kind of redesign strategies should be used in order to increase the SC's robustness. The applicability of the VULA method is demonstrated in the context of a meat SC using discrete-event simulation to conduct the performance analysis.

Keywords:, Supply Chain Management, Vulnerability Profiling, Vulnerability Index, Simulation, Meat Supply Chain

5.1 Introduction

Modern supply chains (SCs) compete with each other on international markets in terms of quality, efficiency, productivity and costs (Christopher and Lee, 2004). Therefore, their imperative is to remove slack from operations, compress cycle times, increase productivity and minimize inventory levels along chains, and at the same time to keep product and customer service quality as high as possible. As a result, SCs have become more vulnerable to disturbances due to unexpected events within companies or in their business environment (cf. Wagner and Neshat, 2010). According to Van der Vorst and Beulens (2002) and Van der Vorst et al. (2009; 2011) food SCs have specific characteristics that make them even more vulnerable to disturbances, such as the food products' limited shelf lives, the high variability in the availability, quality and quantity of raw materials, and the fact that product quality may change as it passes through the SC. This vulnerability makes (food) SC management especially difficult as customers demand robust performances.

In general, SC vulnerability is reflected in SC performances as sudden hiccups or surges in the values of key performance indicators (KPIs). To reduce SC vulnerability, i.e. to attenuate the effects of disturbances in SC processes on the overall performance, it is necessary to design robust SCs (Tang, 2006; Dong and Chen, 2007) that are able to function well in normal business circumstances as well as in the case of disturbances. SC robustness and SC vulnerability are interrelated concepts that are not well defined and fully understood in the literature (Vlajic et al. 2010), especially the relation between vulnerability and robust performances. According to Blackhurst et al., (2005), Kleindorfer and Saad (2005) and Melnyk et al., (2009), a modelling methodology to understand how disturbances will affect a SC, and how far reaching the effects will be, is lacking in the current literature. This is supported by Wagner and Neshat (2010) who state that SC managers still need to be better equipped with methods for measuring and managing SC vulnerability. To address this issue, in this article, a quantitative method is developed to assess SC vulnerability in relation to disturbances in logistical processes over a given time horizon. The method is named the *VULA method* (VULnerability Assessment method). The VULA method considers multiple measures of variability in KPIs and translates them to one overall measure, the vulnerability index, and a vulnerability profile that helps in selecting redesign strategies.

The remainder of the chapter is organised as follows. In section 5.2 we discuss existing assessment methods. Section 5.3 presents the newly developed VULA method. The applicability of the VULA method is illustrated via a case study of a meat SC in section 5.4. In Section 5.5 we discuss the managerial and theoretical implications and in section 5.6 we present the main conclusions and give some directions for future research.

5.2 Assessment of SC vulnerability and performance robustness

In SC management literature the term robustness is defined in many ways, depending on the specific context (see Vlajic et al. (2010) for a detailed literature review). In this chapter we define SC robustness as a desired property of the SC that is reflected in the reliability of its performances. More specifically, SC robustness is defined as the degree to which a SC shows an acceptable performance in its Key Performance Indicators (KPIs) at various levels of uncertainty and disturbances. This definition is in line with Taguchi's idea on robust design based on performance tolerance specifications (Taguchi, 1993; Roy, 2001; Waters, 2007).

In order to arrive at redesign strategies that improve the SC performance robustness, SC vulnerability has to be measured and quantified (Kleindorfer and Saad, 2005; Wagner and Neshat, 2010), as well as analysed. For that purpose specific *vulnerability performance indicators* (VPIs) and specific methods for vulnerability assessment are needed (Melnyk et al., 2009). The following subsections will present the state of the art on both aspects.

5.2.1 Vulnerability performance indicators (VPIs)

In the SC literature various performance indicators that measure vulnerability can be found; Table 5.1 presents an overview of relevant studies. Typical indicators relate to the system's performance such as (fluctuations in) lead time, backorder frequency, costs, customer service, etc. In only a few papers an overall measure of vulnerability is presented. For example, Albino et al, (1998) computed a vulnerability index for production systems based on backorder frequency and increases in the mean transport and throughput time of an order. Wagner and Neshat, (2010) proposed a four-step algorithm using graph theory to calculate a vulnerability index for different industries.

Beyond the SC literature other kinds of vulnerability indicators can be found. The main reference here is Taguchi (1993) who uses variation, signal-to-noise ratio, loss function and economical safety factors as indicators for performance assessment. He uses these indicators to inform the decision whether to alter a defective product or process, or to scrap the defective product and eventually intervene in the design phase. Also, Taguchi shows that conventional concepts of tightening the variation of lower-level characteristics (e.g. raw materials) to make sure that the variation of their higher-level characteristics (e.g. final products) is within its tolerance specifications are very misleading.

In all of these papers the influence of SC disturbances on SC performances is represented by one or more KPIs where for each KPI the mean, variance and/or maximal or minimal value is quantified. Comparison of influences of various disturbances to SC performances is mostly done by a comparison of means of previously defined KPIs (for an overview of KPIs see Table 5.1). However, for a deeper understanding of SC vulnerability, multiple appropriate VPIs should be defined (Melnyk et al., 2009) to make a *vulnerability profile* that indicates how much and for how long the observed KPIs are affected by a disturbance, and what can be expected after a redesign process.

5.2.2 Methods for vulnerability assessment

In the SC management and the SC risk literature vulnerability assessments take place primarily to assess the impact of disturbances on SC performances (Svensson, 2000; Forslund, 2007; Cigolini and Rossi, 2010). Accepted methods that are used for vulnerability assessment and analysis in SC literature are Failure Modes and Effect Analysis (FMEA), SC Event Management (SCEM) (Christopher and Lee, 2004; Waters, 2007), Simulation (Kleijnen and Smits, 2003; Melnyk et al., 2009), and graph theoretic approaches (Wagner and Neshat, 2010), i.e. network models, like Critical Path Methods (CPM) (Herroelen and Leus, 2004).

FMEA is a systematic process meant for reliability analysis which improves the operational performance of production cycles and reduces their overall risk level (Scipioni et al., 2002). Recently, this method is used for the assessment of failures in logistics and SC processes (e.g. Sinha et al., 2004; Tuncel and Alpan, 2010). While being very useful for the identification of the most important risks and disturbances, an important shortcoming of the method is that when applied to processes assessment, it has to rely on experts' opinions and subjective assessments of the probabilities that certain risks will be manifested.

Table 5. 1. Key elements of vulnerability assessments in the SC literature

Authors	Output - KPI measured	Uncertainty/ Disturbance	Method
Levy (1995)	Average and standard deviation of unfulfilled demand Inventory levels Costs of sourcing (increment)	Demand related disruptions Production related disruptions	Simulation Case study
Albino et al (1998)	Lead time Backorder frequency Vulnerability index	Product mix Throughput time	Simulation Case study
Saad and Kadirka-manathan, (2006)	Number of stock-outs Number of undelivered batches Average stock levels and variation in order quantity Number of emergency orders Time to reach steady state (days)	Machine breakdown, Faulty material, late deliveries, stock wastage, incorrect supplied material Change in retail order pattern; lack of demand,	Discrete event simulation
Tomlin (2006)	Costs (as consequence of disturbance) Costs (after implementation of redesign strategy)	Frequency and duration of disruption in supply Supplier reliability Supplier capacity	Markov chain Inventory model
Wilson (2007)	Unfilled customer orders (max and average) Stock fluctuations and goods in transit	Transportation disruption between two echelons in Traditional SC VMI supply chain	System dynamics simulation
Wu et al., (2007)	Costs Lead time (days)	Breakdown in the node of the network	Petri nets Case study
Melnyk et al., (2009)	Disruption periodicity, period, quantity loss, profile, breadth, location Post-recovery output level	Disturbance in general	Concept Discrete event simulation

SCEM is a promising method for risk management that supports risk identification, analysis, selection of adequate responses, and performance monitoring (Otto, 2003). However, in order to be used in practice, this method needs strong ICT support along the SC, which could be an excessively high investment for the companies involved as each company is usually part of many SCs (Mentzer et al. 2001).

Simulation is one of the tools used for disturbance modelling in SCs that can satisfy the need for various levels of modelling detail and output analysis (Kleijnen and Smits, 2003; Saad and Kadirkamanathan, 2006; Melnyk et al., 2009; Hennet and Mercantini, 2010). As such, SC dynamics is easily captured by simulation modelling. Simulation is particularly useful to mimic both a normal regime of work and a disrupted regime of work. It can also be used to evaluate the impact of disturbances and specific redesign strategies intended to protect from, or to manage disturbances. Simulation by itself gives no a priori guidance on what redesign strategies to consider.

Network models are mostly convenient for the analysis of static SCs (e.g. Mo and Harrison, 2005; Dong, 2006), while CPM could be useful for investigating deviations from plans and schedules (e.g. in work of Herroelen and Leus, 2004), but only for simpler SCs and with a limited number of activities (otherwise, the charts become too complex to use). Recently, graph theory is used as a driving vehicle in vulnerability assessment. Using a graph-based algorithm and experts' opinions, Wagner and Neshat (2010) modelled industry specific vulnerability drivers and their mutual relation, which resulted in an estimation of vulnerability indices for various industries. However, to assess the vulnerability of a specific SC, this kind of analysis should be done in more detail, i.e. on the process level.

To conclude, the quantitative analysis of SC vulnerability, considering performance robustness and the assessment of redesign strategies, is in most studies based on the mean of a single KPI, while considering at best a single measure of variability. In the literature it is indicated that higher moments of fluctuations in KPIs should also be taken into account (cf. Tomlin, 2006; Melnyk et al., 2009) as this affects the continuation of business practices; for example, the impact of a disturbance should not only be measured by its magnitude, but also by its duration. Current assessment methods are either too complex or too abstract or too subjective; hence a novel method is needed. In the VULA method, as presented in the next section, we develop a set of VPIs that characterizes SC vulnerability in a multi-dimensional way acknowledging thus the need for different measures of variability (and this in potential multiple KPIs).

5.3 The VULA method

The VULA method consists of three steps and helps in assessing the impact of disturbances to SCs, as well as in selecting appropriate responses and redesign strategies to reduce SC vulnerability. Before we discuss the three steps in section 5.4, we first present the elements that are needed for the vulnerability performance assessment, i.e. calculation methods for vulnerability performance indicators (section 5.3.1), definition of the vulnerability index (section 5.3.2), and definition of a vulnerability profile and response matrix (section 5.3.3).

5.3.1 Definition of vulnerability performance indicators

A robust performance with respect to a specific KPI means that the value of that KPI is kept within tolerance specifications (Taguchi, 1993), i.e. within the *robustness range* (RR). The value x_t that a specific KPI will take at some point in time t during the observation period is not known beforehand as it is a result of fluctuations and disturbances that may happen during the observation period. The RR is the range of 'acceptable' values of x_t, which is bounded by a lower level (LL) and/or upper level (UL) (Taguchi, 1993; Roy 2001; Kleijnen and Gaury, 2003; Waters 2007).

To operationalize this definition of robust performance one should set the length of the observation period, the appropriate RR, i.e. values of LL and UL for each KPI, and the frequency or resolution by which a KPI is updated or recorded. Let T denote the number of updates during the observation period, and as such T denotes also the length of the observation period. The value of T, LL and UL are to be set using historical data and managerial expertise, which is case specific as is the selection of relevant KPIs.

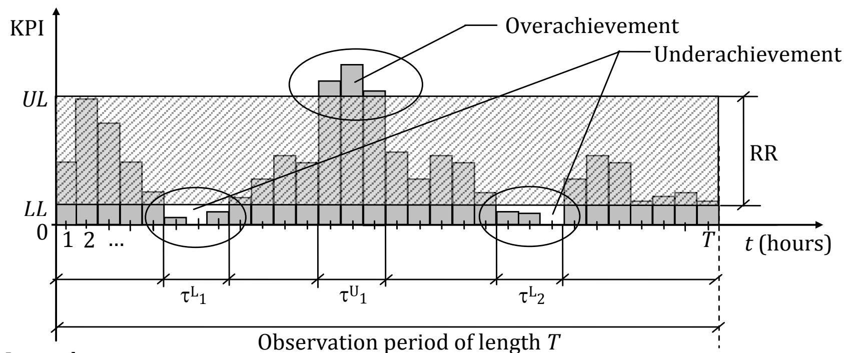
Formally, a system shows a robust performance in a specific KPI over the time horizon $\{1, 2, \ldots, T\}$ when the KPI's value at all points in time t falls in the robustness range: $\forall t \in \{1, 2, \ldots, T\}$: $LL \le x_t \le UL$. Similarly the performance is not robust if for some value(s) of t the value of x_t is below LL or if x_t is above UL. That is if

$$\exists t : (LL - x_t)^+ > 0 \text{ or } (x_t - UL)^+ > 0,$$

where a^+ denote the positive part of expression a, i.e. $a^+ = \max\{0, a\}$.

Because of strong pressure from competitors, strict demands from customers or particular industrial norms, the RR of modern SCs could be very narrow. In this case, unplanned events could easily result in KPI values that are out of range, indicating SC vulnerability. Moreover, and for the same reasons, UL and LL values could change in time (e.g. RR of availability of food products could change within a year due to change in demand or seasonal effects). For some KPIs either LL or UL may be unspecified i.e. UL and LL may be set to infinity or minus infinity, respectively.

In the graphical example in Figure 5.1 one considers the inventory level as a relevant KPI. The value of LL could be set to the amount of safety stock a company applies and UL to the assigned storage capacity for that particular product. The KPI inventory level shows a robust performance if the inventory level stays between LL and UL over the entire observation period: i.e. for all $t \in \{1, 2, \ldots, T\}$: $LL \le x_t \le UL$. When the inventory is less than LL the risk of an inventory shortage is to be expected, and when it is higher than UL the inventory exceeds the allotted storage capacity. In food SCs this can have an immediate negative effect: products that cannot be stored under the right conditions (and cannot be moved to storage easily) may deteriorate in quality or become spoiled such that they no longer meet the food safety requirements. In both cases, the consequences could be expressed in monetary terms (e.g. cost of inventory shortage, or product waste), time (duration of stock-outs and additional stock-keeping) and magnitude (shortage quantity or surplus quantity).



Legend:
T – duration of observation period
τ^L, τ^U – vulnerability periods (when KPI values are out of robustness range)
UL – upper level of KPI robustness range
LL – lower level of KPI robustness range
RR – robustness range

Figure 5. 1. Inventory level: example of robust performances and robustness range

The larger the value of $(LL - x_t)^+$ and $(x_t - UL)^+$, the more vulnerable the SC is with respect to this KPI. Moreover the more (successive) periods t in which $(LL - x_t)^+$ and $(x_t - UL)^+$ is positive, the more vulnerable the SC gets. Similarly to Weber (2002), we argue that it is better to consider two types of VPIs: Time related performance indicators (TPIs), and Magnitude related performance indicators (MPIs).

5.3.1.1 Time related performance indicators (TPIs)

For a specific KPI, several *time performance indicators* (TPIs) should be measured, such as the duration of stock-outs or excessive inventory (Weber, 2002), the variability in the lead time (anticipated versus confirmed lead time – Forslund et al., 2009), and the duration of the period of vulnerability (Melnyk et al. 2009). TPIs are performance indicators that measure the duration of deviations from the RR within the observation period of length T, and in this chapter the following five TPIs are considered:

TPI1 = the total vulnerability time (TT) = sum of all time units in the observation period where KPI value is out of RR, (TT)

$$\mathrm{TT} = TT^L + TT^U = \sum_{t=1}^{T} I(x_t < LL) + \sum_{t=1}^{T} I(x_t > UL).$$

TPI2 = the average duration of a vulnerability period (TA)

$$TA = \frac{TT^L + TT^U}{TN^L + TN^U},$$

where TN^L and TN^U is the total number of vulnerable periods in case the value of KPI $x_t < LL$ respectively $> UL$. Precise formulas are found in the Appendix 5.1.

TPI3 = the total number of vulnerability periods (TN)

$$TN = TN^L + TN^U.$$

TPI4 = the maximal duration of a vulnerability period (TM)

$$TM = \max\left\{TM^L, TM^U\right\},$$

where TM^L and TM^U is the maximum duration in case the KPI is below LL respectively above UL. Using the definitions found in the Appendix 5.1 we have

$$TM^L = \max_{n=1,\ldots,TN^L} \tau_n^L, \quad \text{and} \quad TM^U = \max_{n=1,\ldots,TN^L} \tau_n^U.$$

TPI5 = the fraction of time in the observed time period that the KPI is out of the RR, (TF)

$$TF = \frac{TT}{T}.$$

5.3.1.2 Magnitude related performance indicators (MPIs)

For a specific KPI, several *magnitude performance indicators* (MPIs) should be measured, such as the difference between the quantity of inventory actually available and the inventory quantity needed (Weber, 2002), the number of data points out of the RR (and their position) (Nelson, 1994), and the number of units that is not delivered by a supplier as a result of the disruption (Melnyk et al., 2009). MPIs are performance indicators that measure the magnitude of deviation from RR over the observation period of length T, and in this chapter the following indicators are considered: total magnitude, average magnitude, and maximal magnitude. In addition to these indicators one could split the indicators into separate indictors for the case of lower and upper deviation from RR:

MPI1 = the total magnitude of the deviations from RR, which is the sum of deviation of x_t below *LL* or above *UL*, (*MT*)

$$MT = \sum_{t=1}^{T}(LL - x_t)^+ + \sum_{t=1}^{T}(x_t - UL)^+ .$$

MPI2 = the average magnitude of the deviations from RR, (*MA*)

$$MA = \frac{MT}{TT} .$$

MPI3 = the maximal magnitude of underachievement and of overachievement (*MM*)

$$MM = \max\{MM^L, MM^U\}$$

where

$$MM^L = \max_{t\in\{1,\ldots,T\}}(LL - x_t)^+ \text{ and } MM^U = \max_{t\in\{1,..,T\}}(x_t - UL)^+ .$$

5.3.2 Definition of the vulnerability index (VI)

The VPIs (TPIs and MPIs) discussed in the previous section can be used to assess and characterise SC vulnerability related to any KPI. This could be easily done in a simulation study by defining a set of scenarios *S* related to relevant types of disturbances. Therefore it is of interest to study the sources of vulnerability as this gives an indication of what types of disturbances should be part of the scenarios. In food SCs the perishable nature of the products is an important source of vulnerability, and therefore three types of disturbances in logistics processes are distinguished (Vlajic et al. 2012): (1) disturbance in time (e.g. longer lead time than planned, delays), (2) disturbance in quantity (e.g. to get delivered less or more than ordered, or to produce less or more than planned), and (3) disturbance in product quality (e.g. the delivered goods are not of the quality ordered). Each disturbance is characterized by a *probability* that the disturbance occurs (during a specific time interval) and its *size*.

Each *scenario* in set *S* is defined as a realization of disturbances in one or more SC processes and as such, a scenario is characterized by a probability (*p*) that a given disturbance (*d*) of a given size (*c*) happens (e.g. there is a chance of *0.36* that a truck will arrive with *30 minutes delay*):

$$S = \{d,\ p, c\}$$

Similar to Paulsson, (2007), who describes SC vulnerability through a scenario space and an outcome space, we describe SC vulnerability as set of two components: a set of scenarios *S* and a set of VPIs:

Vulnerability = {*S*, set of VPIs},

where

Set of VPIs $\subseteq \{TPI\,1,\ldots TPI\,5, MPI\,1,\ldots, MPI\,3\}$

For all VPIs the following holds: the worst-case scenario is the scenario in which the value of the respective VPI is highest. In order to compare the outcomes per scenario, the values of the VPIs TPIs and MPIs are scaled by setting the value to 100 for the worst-case scenario.

In principle, some VPIs have more discriminating power than others to assess the vulnerability with respect to a particular KPI. This means, by using expert opinions it is possible to select the most discriminating VPIs and to assign weights to them, and to estimate a *VI* for each scenario. Next for each VPI *j* in the set of selected VPIs, depending on its importance and priority, a corresponding weight w_j is assigned, such that $0 \leq w_j \leq 1$ and $\sum_{j \in \text{Set of VPIs}} w_j = 1$.

In principle all TPIs and MPIs could be included, but depending on the risk preference of managers, the most appropriate should be selected (e.g. risk averse managers would try to avoid situations that could cause high vulnerability, so they would select TPI4 and MPI3 as the most important). The weighted sum of the selected VPIs results in the (VI_i) of each scenario *i*:

$$VI_i = \sum_{j \in \text{Set of VPIs}} VPI(i, j) \cdot w_j$$

where *VPI(i,j)* indicates the value of VPI *j* in scenario *i.*

This definition of the *VI* is similar to the definition of the Overall Evaluation Criterion in Roy (2001).

5.3.3 Definition of vulnerability profile and response matrix

A proper interpretation of VPIs requires sufficient information about the impact of disturbance, i.e. a vulnerability profile. The vulnerability profile indicates the *vulnerability level* (normal or disrupted) and *type of vulnerability*: e.g. high impact for a short period or a long-lasting low impact, as well as the expected frequency of an impact (cf. Nelson, 1994; Melnyk et al., 2009). As such, the *vulnerability profile* has to be based on the scenario analysis of each indicator with respect to the magnitude and time dimensions. For the selected set of indicators from both dimensions it is necessary to determine a scale. In the SC risk management literature, the probability and impact scales are often based on the categorization of indices to low, medium and high values. In analogy with a probability/impact matrix (Norrman and Lindroth, 2004; Waters, 2007), we construct a similar matrix for *vulnerability profiling and response selection* using these VPIs (Table 5.2).

Table 5. 2. Example of vulnerability profile and response matrix

		Magnitude Performance Indicators		
		Low	Medium	High
Time Performance Indicators	Low	ROBUSTNESS ZONE – *No* response -	Normal regime – Reductive response -	Disrupted regime - Reductive response -
	Medium	Normal regime - Preventive response -	Normal regime - Reductive response -	Disrupted regime - Reductive response -
	High	Disrupted regime - Preventive response -	Disrupted regime - Preventive response -	Disrupted regime - Preventive and reductive response -

The upper-left section in the matrix (Table 5.2) denotes acceptable performances with a low vulnerability level. This section represents the *Robustness Zone* – it is characterized by low values of the TPIs and MPIs, so it indicates an ideal regime in the vulnerability profile. The lower rightmost section represents the most vulnerable zone, with high values of MPIs and TPIs (vulnerability profile: high, long lasting impact of disturbance).

The vulnerability profile should also give direction for the response and the selection of appropriate redesign strategies. In the literature, many response concepts[4] are discussed; for an overview we refer to Vlajic et al. (2012a). Generally, response concepts are based on two elements: what is the occurrence frequency of the disturbance and, what is the consequence of the disturbance? We classify response

[4] Terms “Response concept” and “Disturbance management concept” have the same meaning ant they are interchangeably used in this thesis

concepts in two groups: *preventive concepts*, focused on the reduction of disturbance frequency, and *reductive concepts*, focused on the reduction of impact of disturbances. Each concept contains a number of redesign principles and strategies, further classified according to the SC design elements, e.g. strategies that aim to change the SC structure or the SC planning and control system. In line with Hopp (2008), who made a diagram of four response concepts based on the probability of occurrence and the expected severity of consequences, we assign preventive and reductive response concepts based on the vulnerability profile, i.e. values of TPIs and MPIs (Table 5.2).

5.3.4 Steps of the VULA method

After a SC analysis has been done the VULA method can be applied to the selected KPI. The VULA method comprises the following three steps:

1) First, the RR for a specific KPI is specified and historical data is used to assess the performances on VPIs.
2) Second, a number of scenarios are defined related to prominent disturbances. Using historical data, complemented with results from simulation studies, the VPIs are evaluated for each scenario. By scaling and weighting the different VPIs a *VI* is calculated, which quantifies the SC vulnerability. This *VI* may give a first insight on whether action should be taken, but it gives no direction to what kind of redesign strategies should be considered.
3) The third step offers guidance in selecting redesign strategies through a vulnerability profile and response matrix that indicates what kind of response and redesign strategy is most likely to reduce SC vulnerability.

To demonstrate the applicability and workings of the VULA method we applied it in a case study of a meat SC.

5.4 An illustrative case – applying the VULA method to a meat SC

In order to test and demonstrate the VULA method, a case in the meat SC is used as an illustrative example. In this section the case is briefly summarized, the most relevant KPIs are addressed, as well as the sources of vulnerability, and typical disturbances. Next, in subsequent subsections we demonstrate the three steps of the VULA method.

The meat SC under consideration (Figure 5.2) consists of suppliers (mainly slaughterhouses), a transportation company, a meat processing company and its customers. The meat SC is suitable as an illustrative example because it is characterized by a high variability in the availability, quality and quantity of raw materials, and by a relatively wide assortment of final products (Wognum et al., 2009). Furthermore, meat products are perishable and food quality regulations put high pressure on time constraints as well as on production, packaging, warehousing and transport processes. These are significant sources of vulnerability.

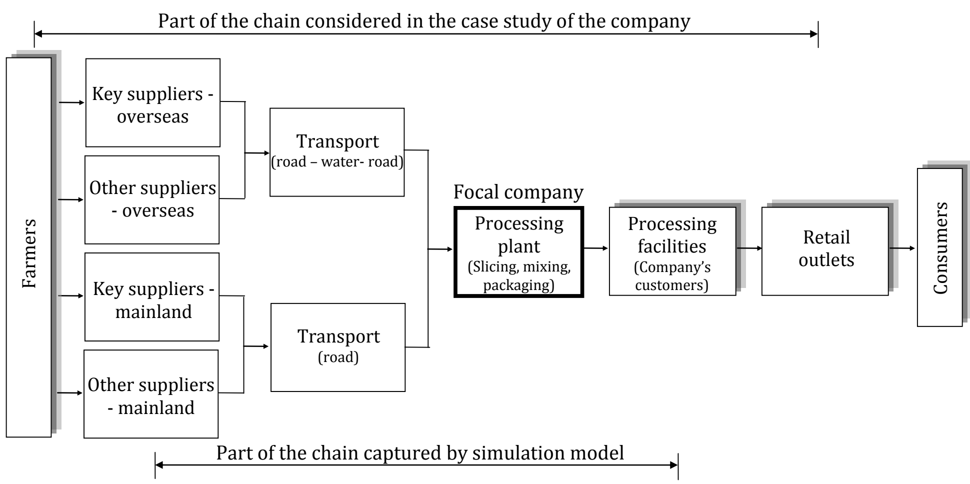


Figure 5. 2. The meat SC

A very vulnerable member in this SC is the fresh meat processor, as supply and demand are uncertain and storage is hardly possible for fresh meat products due to strict regulations regarding freshness and safety of the products. The processor deals mainly with one type of raw material, which is to be disassembled (sliced and cut) to several products during production. As products have to be processed while fresh the company is practicing principles of JIT sourcing, i.e. the daily delivery schedule is synchronized with production speed whilst the company is keeping low inventory levels of raw material (less than one third of a day). Raw materials are delivered multiple times a day, according to a specified schedule.

The main disturbances are occur with the suppliers (uncertainty in availability and variation in quality and quantity of material) or during transportation (i.e. traffic jams, technical failures in cooling raw materials during transport) and they can ultimately cause stoppages of production or lower productivity on a daily basis.

To make the company less vulnerable to such disturbances a number of redesign principles could be applied. For example, product inspection happens upon arrival of the products (before the material gets stored) and prior to processing individual items of raw material, they are again visually inspected and sorted according to processing type: on the automatic production line or manual processing at a separate production line. Further the daily production plan is based on 95% utilization rate of the automatic production line as the supplied quantity may deviate from the ordered quantity and because the speed at which the raw material can be processed depends on the quality of the products.

5.4.1 VULA-step 1: Performance assessment of the meat processor

The most important KPI for the focal company is gross profit (revenue minus the cost of goods sold), which is a good measure for a SC with high costs of resources (McAnally, 1963) such as the meat industry (Morrison, 1997). In this section we demonstrate the VULA method with respect to the gross profit as it is the primary objective.

The VULA method is applied over a (rolling) time horizon of T = 50, working days, as the company considers a planning horizon of at most 2 to 3 months to be realistic. Beyond 3 months, demand and supply may have dramatically changed. According to the CFO the company becomes vulnerable when the daily gross profit drops below the fixed overhead costs of 44,000 euro per day. Hence LL= 44,000 euro and $UL = \infty$. All eight VPIs (five TPIs and three MPIs) presented in section 3 are included in the vulnerability analysis. The UL is set at infinity for TT^U, TN^U and TM^U, while MM^U is zero.

Historic data on daily profits is available to evaluate the values of the VPI, but for the next step of the VULA method we have developed a discrete event simulation model of the meat SC in simulation software Enterprise Dynamics. The simulation model enables the simulation of several scenarios with disturbances.

5.4.2 VULA-step 2: Vulnerability index of the meat processor

In this step a set of scenarios relating to the main disturbances is defined, using inputs of the CEO, CFO and logistics managers. Next to and based on their valuable inputs an influence diagram is constructed showing the most relevant factors that influence gross profit. In Figure 5.3 one finds a representation of it indicating the dependent variables and independent variables (other KPIs that influence the gross profit), such as the availability of raw material and the quality of the raw material. The influence diagram helped in specifying the simulation model of the SC depicted in Figure 5.2 (which excludes the farmers and consumers).

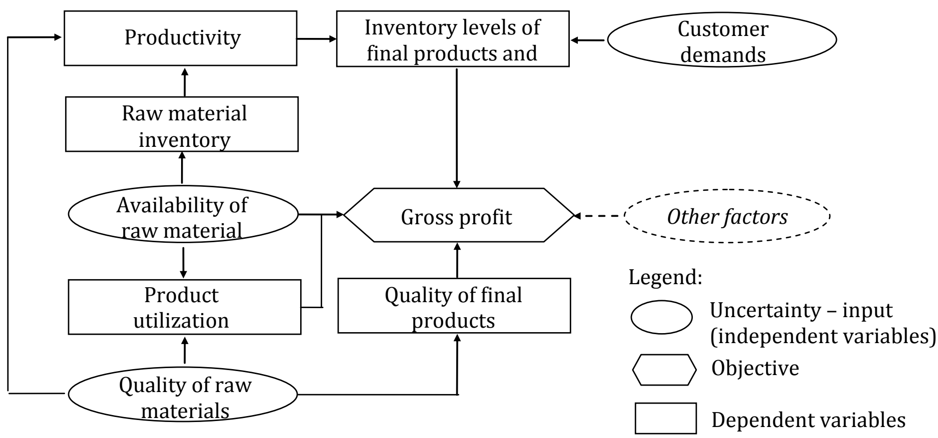


Figure 5. 3. Simplified overview of the influence diagram

5.3.2.1. Scenarios of disturbances

The main operational and planning processes as well as the typical practices of the meat processing company are incorporated in the simulation model (in line with the recommendation of Law and Kelton, 2000). To illustrate the VULA method three types of working regimes are distinguished:

- ideal regime – a regime of work in which no disturbances (i.e. unexpected events) occur;
- normal regime – a regime of work in which moderate unexpected fluctuations in the supply of raw materials are part of the business;
- disrupted regime – a regime of work in which severe disturbances such as operational failures may happen in the sourcing and delivery of raw materials.

Fluctuation and disturbances are related to (1) the transportation time, (2) the supplied quantity, and (3) the supplied quality of the raw material. Hence, we consider six scenarios on top of the base scenario (scenario S0) that represents an ideal regime of work. Scenario S1, S2, and S3 relate to the normal regime with fluctuations in time, quantity and quality respectively. Similarly, scenarios S4, S5, S6 are defined under a disrupted regime of work.

Fluctuations in time, quantity and quality are modelled by respectively Triangular, Normal and Bernoulli distributions. In scenario S4 and S5 failures implying only partial deliveries that happen according to Bernoulli distributions with different parameter values for the different types of suppliers. Similarly in scenario S6 a failure in product quality is modelled but then a quality failure implies that raw material can still be processed on the slow and more expensive manual production line. Based on a limited data set and additional interviews with the logistics and operations managers of the focal company we have estimated the input data for each scenario (Table 5.3).

Table 5. 3. Scenarios S1 to S6: probability distributions of fluctuations and failures

Scenarios		Suppliers		Transport from a supplier	
		Key	Occasional	Mainland	Overseas
Fluctuations in:	S1 –time (h)			Triang. (1; 0; 2)	Triang. (1; 0; 2,5)
	S2 – quantity (kg)	Normal (2100; 105)	Normal (2100; 105)		
	S3 – quality (level: items)	Bernoulli (0.9)	Bernoulli (0.9)		
Failures in:	S4 – timing (no delivery)			Bernoulli (0.01)	Bernoulli (0.05)
	S5 – quantity (partial delivery)	Bernoulli (0.5)[1]			
	S6 – quality				
	• Items: manual processing	Bernoulli (0.80)	Bernoulli (0.20)		
	• Truck load damaged	Bernoulli (0.02)	Bernoulli (0.02)		

Key: Triangular distribution (mean delay, minimum, maximum delay); Normal distribution (mean and stan deviation); Bernoulli distribution (probability that an item of raw material can be processed automatica
[1] - Probability of failure defined for overseas supplier

5.3.2.2. Output analysis: scenario analysis based on VPIs

Each of the above scenarios was simulated for 100 separate runs of 50 working days (including 5 days for warming up) to get accurate estimates of MPIs, and TPIs with respect to the gross profit. For example, in Figure 5.4 the results of two simulation runs are displayed on a graph: the profit in each period is shown on the vertical axis and the RR is marked.

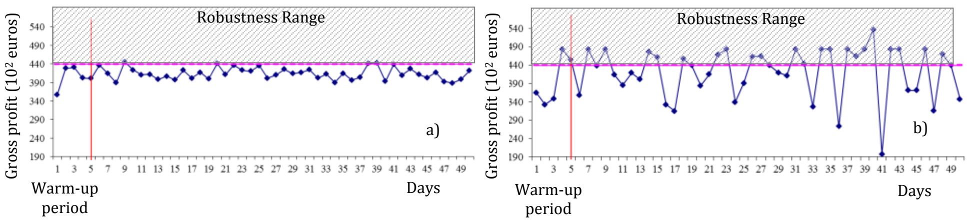


Figure 5. 4. Values of the gross profit during fluctuation in delivery quantity in the 12th simulation run (Scenario 2, figure a) and during transport disturbances (Scenario 4, figure b)

In Table 4 one reads the scaled values of the VPIs (TPIs and MPIs), taking thus a value between 0 and 100. The VPI (i.e. TPI or MPI) for the most vulnerable scenario is set to 100, and the other VPIs get a value proportional to this figure.

Table 5. 4. Indexed values of MPI and TPI per scenario (value of 100 represents the most vulnerable scenario with the respect to the indicator)

Scenarios	Average daily profit	Magnitude related performance indicators			Time related performance indicators				
		MPI1	MPI2	MPI3	TPI1	TPI2	TPI3	TPI4	TPI5
S0	86.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S1	86.4	0.2	7.2	39.7	2.0	2.9	6.5	4.4	2.0
S2	91.5	39.4	37.4	27.6	99.5	92.8	20.6	100.0	99.5
S3	88.0	12.9	12.2	9.2	100.0	100.0	19.1	100.0	100.0
S4	88.9	47.6	93.4	100.0	48.5	7.3	100.0	5.2	48.5
S5	100.0	100.0	100.0	95.4	94.7	47.6	35.2	100.0	94.7
S6	90.0	32.2	31.3	29.7	97.5	66.2	26.6	100.0	97.5

TPIs and MPIs have discriminating power such that based on their values one may assess the impact of the disturbance that has happened, provided that there is a database with recorded disturbances and in the best case also their potential causes. This is particularly useful in monitoring a SC and signalling any potential problems, similar to SCEM.

In the case we considered, based on the indexed daily average gross profit (in the second column, Table 5.4), the SC is most vulnerable in the case of pure quantity disturbance, i.e. Scenario S5: a failure at one of the key suppliers. However, the indexed average daily profit alone shows that other disturbances have to be considered as well: all index scores are between 86 and 92. As the differences are small one may question which scenario most requires a manager's attention and whether these disturbances should be managed equally? To answer this question, the *vulnerability index* and *vulnerability profiling* are used, as showed in the VPIs in the other columns in Table 5.4.

5.3.2.3. Vulnerability index (VI)

To illustrate the approach MPI3 and TPI2 are selected and importance weights are assigned (subjectively in line with manager's risk attitude). The weights of the VPIs, the values of the vulnerability index *VI*, as well as the ranking of the scenarios based on *VI* are presented in Table 5.5.

Table 5. 5. Vulnerability index per scenario

Scenario	Selected VPI		Vulnerability index (VI_i)	Rank of scenarios
	MPI3 $w_1 = 0.55$	TPI2 $w_2 = 0.45$		
S0	0.0	0.0	0.0	7
S1	39.7	2.9	23.2	6
S2	27.6	92.8	56.9	3
S3	9.2	100.0	50.1	4
S4	100.0	7.3	58.3	2
S5	95.4	47.6	73.9	1
S6	29.7	66.2	46.1	5
			Max: 73.9	

For the chosen combination of VPIs and related weights (which reflect an attitude of a risk-averse manager, or company policy, for example) the most critical scenario appears to be S5, followed by S4 and S2. The fact that S4 has a higher ranking than S2 is explained by the fact that MPI3 has a higher weight than TPI2. The ranking of the scenarios provides managerial information on how fluctuations and disturbance are affecting the vulnerability of the company and the SC.

5.4.3 VULA-step 3: Vulnerability profile and response matrix

To assess whether the SC is functioning in a normal or disrupted regime of work, and what kind of vulnerability is in question, the vulnerability profile is required. Let us give some examples.

In scenario S5, a few VPIs are close to 100 – they indicate a high vulnerability due to high potential losses and long vulnerability periods; i.e. the company has low robustness of gross profit. However, having a high score on, for example, maximal magnitude (MPI3) is not unique to scenario S5. Scenario S4 shows the largest value on MPI3; the highest potential loss in a single event (MPI3) could happen due to transportation failures. However, despite the fact that the company suffers frequently from disturbances in transport (TPI3), the average duration of the vulnerability period is low (TPI2), which indicates that the company is affected by failures of transport for only a short period of time, though frequently (TPI5).

High values of TPI1, TPI2, TPI4 and TPI5 together with a low value of TPI3 indicate that a company is exposed to a single long period of vulnerability because of fluctuations in quality of raw material (S3). However, low values of MPIs indicate low potential losses in this scenario. In comparison with this scenario, scenario S6 indicates a shorter vulnerability time (values of TPIs), but higher potential losses (values of MPIs).

In Table 5.4, the vulnerability of scenarios can be assessed also by analysing values column wise (per indicator). For example, the maximal duration of vulnerability periods (TPI4) and the total vulnerability time (TPI1) indicate that next to failures of key suppliers (S5) and quality failures (S6), fluctuations in quantity and quality could cause very long periods of vulnerability for the company. However, the values of average magnitudes (MPI2) show that S5 actually represents a higher threat, while scenarios (S2, S3 and S6) could be seen as medium level threats to competitiveness.

This short analysis represents a quick evaluation of the SC vulnerability to specific disturbances. Next to the most vulnerable scenario (S5), it appears that scenarios S2, S3, S4 and S6 have high vulnerability, but different vulnerability profiles.

In the last step, to increase performance robustness, the search for the most appropriate response and redesign strategy starts in Table 5.2. Based on expert opinion, values of MPI3 and TPI2 were categorized into high, medium and low and each scenario is assessed based on these values and assigned to the appropriate field in the matrix (see Table 5.6). For example, scenario S5 has high MPI3 and medium TPI2 values, resulting in the conclusion that reductive redesign principles should be applied. Hence, the SC structure could be changed (e.g. increase the width of the supply base) or the organization structure could be changed (e.g. use risk-sharing supply contracts); an extended overview of available redesign principles can be found in Vlajic et al. (2012a). In this way, the focal company could redesign its SC in order to reduce the impact of suppliers' speculations and improve controllability over the SC by increasing their supply options.

However, scenario S2, though characterised only by fluctuations in supplied quantities, shows relatively high vulnerability as reflected by TPI2. In this scenario, a preventive response is desirable, e.g. to use economic supply incentives to cultivate additional suppliers (Tang 2006), especially when one considers the limited supply base in meat industry. This way, scenario S2 should move upper left field in the matrix towards a normal regime. In S4 (with high MPI3 and low TPI2) the safety stock of raw material could be optimised within food safety requirements (constraints related to raw material freshness), so scenario S4 would move to leftward in the matrix or to the robustness zone.

Table 5. 6. Example of vulnerability profile and response matrix

		Magnitude Performance Indicator: MPI3		
		Low (0 – 25]	Medium (25 – 80]	High (80 – 100]
Time Performance Indicators	Low (0 - 25]	ROBUSTNESS ZONE **S0** – *No* response -	Normal regime **S1** – Reductive response -	Disrupted regime **S4** - Reductive response -
	Medium (25 - 65]	Normal regime *S3-a* - Preventive response -	Normal regime - Reductive response -	Disrupted regime **S5** - Reductive response -
	High (65 - 100]	Disrupted regime **S3** - Preventive response -	Disrupted regime **S2, S6** - Preventive response -	Disrupted regime - Preventive and reductive response -

To get more insight into the impact of redesign principles on the robustness of company performances, sensitivity analysis on model input data can be conducted. For example, if we consider redesign for scenario S3: an improvement of the quality of raw materials of 15% (scenario S3-a) in a shipment would not affect MP3 much (the value of the indicator would be almost the same), but it would contribute to a significant reduction of TPI2 (the value of the indicator would be reduced by more than 50%). Position of the scenario S3-a is in the upper field comparing to the position of the scenario S3 (Table 5.6), which indicate improvement after redesign. However, by using this strategy the company would not be in robustness zone! The impact of every potential strategy could be assessed in the same way, resulting in managerial insight to select the best redesign principles in a particular case.

5.5 Discussion

As stated in the introduction SC managers need to be better equipped with methods of measuring and managing SC vulnerability (Wagner and Neshat, 2010). The VULA method could help managers to assess vulnerability levels of the company, identify how much the company would underperform in the case of a disturbance, how often would that happen and how long would it last, and ultimately give direction to what kind of response concepts to consider for each type of disturbance. The method studies SC vulnerability and would incite SC members to look more closely at their sources of vulnerability. In that way, top management gets more reliable information about the "health" of the company, and they can use it to decide whether a process redesign is appropriate and what kind of redesign strategies to use in order to improve SC robustness. The process of thinking about one's vulnerabilities in a structured way, as presented in Vlajic et al. (2012a), is a first step in redesigning a SC towards a robust SC. The VULA method as presented in this chapter provides the next step.

However, there are some issues concerning the method that merit further reflection. First of all, the impact of a specific disturbance to SC performance in practice depends upon the specific characteristics and the design of the SC. Hence, the best redesign strategy depends upon those specific characteristics. It is therefore very difficult to define generic best redesign strategies related to specific disturbances, which is something that would further strengthen the tool. Second, although in our method the disturbance detection is automated and quantified, the weighting of the VPIs still requires expert judgement and is thus subjective. Maybe risk preference measures would indicate and drive the selection of MPIs and TPIs, as well as their weights. Future research may be directed to the development of more VPIs as well as a more advanced method to determine weight factors in the vulnerability index. Additional measures, such as a conditional risk could be used as well (cf. Erkut and Verter, 1998). Also other statistical measures for disturbance detection and redesign improvement, such as kurtosis (e.g. Boger et al., 2001), could be useful. Third, there should be enough historical information available in the company or SC to conduct the performance assessment. This shall be overcome once more data is collected through applying the method. This again will result in more insight into disturbance frequencies and impacts as well as into the most important sources of vulnerability. It therefore becomes a learning system for the organisation resulting in more and more robust performances over time.

5.6 Conclusion

Robustness of food SCs is an understudied but relevant area since food SCs have, in comparison to most other SCs, a relatively high vulnerability level. To assess SC vulnerability and to investigate how vulnerability affects the SC, we have presented the VULA method. This three step method goes beyond comparing averages of some KPIs (which is a limitation of many previous studies) but also investigates different measures of variability of both the duration of impacts from disturbances and the fluctuations in magnitude. In particular, in food SCs this extension is crucial as fresh products flowing through a food SC are perishable and the companies involved must obey strict food safety restrictions (e.g. for freshness). We have illustrated the applicability of the method in a meat SC in which a simulation model was built to assess performances in different scenarios. The managers from the case company concluded that the VULA method contributed significantly to their understanding of their vulnerability, and helped them in finding relevant redesign strategies. However, additional research is needed to validate and extend our findings. More VPIs and a more advanced method is to be developed to determine weight factors for the calculation of the vulnerability index and the vulnerability profile and response matrix. More case studies can be done in the food industry to get more insight in the relationship between different kinds of disturbances and redesign strategies.

Appendix 5.1

In this appendix we define precise formula's to derive the start and end of each period and the number of vulnerable periods therefor we introduce the function I(a): it takes value 1 if Boolean expression a is true and zero if a is false. By superscript L and U we discriminate between periods of KPI values below LL and above UL.

The first time interval of low performance start at

$$s_1^L = \min_{t\in\{1,\ldots,T\}} \left(t : I(x_t < LL)\right),$$

and ends at time

$$e_1^L = \min\left\{T, \min_{t\in\{s_1^L,\ldots,T-1\}} \left(t : I(x_{t+1} \geq LL)\right)\right\}.$$

Similarly for $n>1$, the n-th interval of low performance starts at

$$s_n^L = \min_{t\in\{e_{n-1}^L+1,\ldots,T\}} \left(t : I(x_t < LL)\right)$$

and ends at time

$$e_n^L = \min\left\{T, \min_{t\in\{s_{n-1}^L,\ldots,T-1\}} \left(t : I(x_{t+1} \geq LL)\right)\right\}.$$

The length of the n-th time interval is thus $\tau_n^L = e_n^L - s_n^L$.

The number of time intervals of low performance is TN^L, and equals the number n of the last interval after which the performance stays at or above LL till the end of the observation period, or formally:

$$TN^L = \min_{t\in\{e_{n-1}^L+1,\ldots,T\}} \left(n : \prod_{t=e_n^L+1}^{T} I(x_t^L < LL) = 0 \right).$$

The definitions of s_n^U, e_n^U, τ_n^U, and TN^U for the case of overachievements is done in similar way by replacing in the above definitions the superscripts L into U and all "<LL" and "≥ LL" are changed into ">UL" and "≤ UL" respectively.

“There will come a time when you believe everything is finished.

That will be the beginning.”

Louis L’Amour, (1908 – 1988)

6. Discussion and conclusions

Jelena V. Vlajić

“Robust food supply chains, An integrated framework for vulnerability assessment and disturbance management”, PhD Thesis, Wageningen University

The overall objective of this research was twofold. We aimed to contribute to the scientific community in the SCM research area to better understand and assess supply chain (SC) vulnerability, as well as to propose a structured way to select and use disturbance management principles (DMPs) and corresponding redesign strategies that will improve the performance robustness of food SC. We also aimed to contribute to the professional community by helping companies in the food industry to evaluate their current state of vulnerability, to find the underlying causes, and to improve performance robustness. To reach these objectives, we formulated the following research questions (RQ):

RQ1:	*What are the main research challenges related to (food) SC robustness?*
RQ2:	*What are the main elements that have to be considered in the design of robust SCs and what are the relationships between these elements?*
RQ3:	*What is the relationship between the contextual factors of food SCs and the use of DMPs?*
RQ4:	*How to systematically assess the impact of disturbances in SC processes on the robustness of (food) SC performances?*

The answers to these research questions can be found in Chapters 2 to 5. In this chapter we summarise our findings and discuss how the answers to these questions contribute to the research objectives. Therefore, Section 6.1 presents the answers to the research questions. In Section 6.2 we integrate all the findings and present an integrated framework for designing robust food chains. Section 6.3 discusses the main theoretical contributions. In Section 6.4 we indicate the research limitations of the project and give suggestions for future research. Finally, in Section 6.5 we present the managerial implications of this research.

6.1. Answers to the research questions

Findings RQ1: main research challenges in (food) SC robustness

Research question one is answered in Chapter 2. To answer the question we first reviewed the literature for existing definitions of *robustness* as well as the contexts in which robustness is researched. An extensive literature review showed that robust(ness) is a popular term, used in many disciplines, as well as in SCM literature. In SCM context, robustness is vaguely defined, and mostly perceived in relation to concepts like *vulnerability* and *flexibility*. The review shows SC robustness is studied at two levels: conceptual and modelling. At the conceptual level, robustness is mainly seen as a property of the system under study or as a redesign strategy that can be used to improve the system performance. At the (quantitative) modelling level, it is the robustness of the model design and/or the robustness of the (quantitative) model solutions that are considered. To conclude, the main research challenges identified in SC robustness (Vlajic et al., 2010) are as follows:

1. Robustness is an important factor for achieving SC network competitiveness but is vaguely defined in the literature. Therefore, SC network robustness should be more *precisely defined* and related to *key performance indicators* (KPIs) of businesses to guide SC network improvement programmes.
2. All relevant *external factors* should be identified in the case of a specific SC network and their influence on vulnerability should be investigated for specific cases.
3. In order to work with SC network robustness, it is useful to establish *degrees of SC network vulnerability*. As, SC network vulnerability is caused by specific types of disruptions, a more precise *categorisation of disruptions* in their relation to the strategic, tactical and operational level of decision making would be useful.
4. There is a need for a *systematic overview of (re)design strategies* that may improve SC network robustness (and that considers all elements of the SC network design) and a list of appropriate criteria to support the selection of the right redesign strategy in a specific case.
5. When modelling and assessing the robustness of food SC network the *specific characteristics of these networks* should be incorporated in the model.
6. Using a *robustness index* (i.e. a measure that quantifies the extent to which a company or SC shows robust performances when exposed to uncertainty and disturbances) can be useful in quantitative modelling and it can be a powerful tool for measuring SC network robustness. Till now, there have only been a few attempts to develop such a tool.

Findings RQ 2: A research framework for designing robust SCs

The second research question is answered in Chapter 3, where a research framework is presented for the design of robust SCs, including definitions and classifications of its elements. The framework is the result of a literature search and open and semi-structured interviews with domain experts regarding particularities related to the food industry.

In this chapter (Vlajic et al., 2012a), SC robustness is defined as follows:

SC robustness is the degree to which a SC shows an acceptable performance in (each of) its Key Performance Indicators during and after an unexpected event that caused a disturbance in one or more logistics processes (Section 3.2).

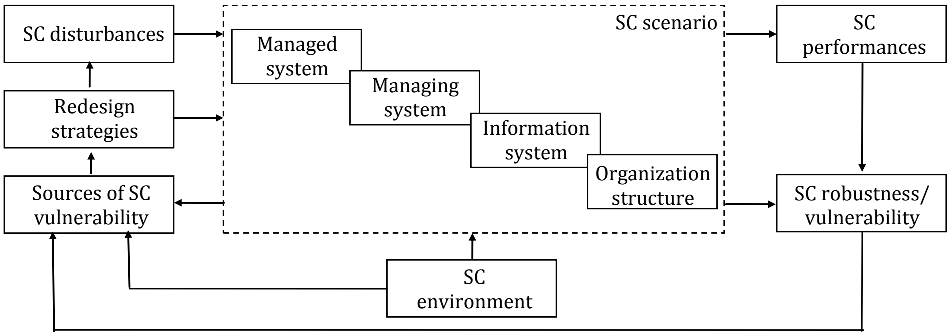


Figure 6. 1. Research framework for designing robust (food) SCs

Via an extended literature review, we identified, defined and classified a number of key elements that should be incorporated in the research framework, and explained the relationships between the elements (as presented in Figure 6.1). The main findings concerning the three basic elements are as follows:

a. *SC disturbance* is a minor or major deviation, or failure of one or more logistics processes triggered by unexpected events in the SC or its environment resulting in poor performance of the process itself, company and potentially along the SC in a given time period (Section 3.3.1).

SC disturbances are characterised by: (1) the frequency of occurrence, (2) the possibility of detection, (3) the impact on SC performance, (4) the cause of the disturbance (expressed in quality, quantity or time dimension) and (5) the size of the disturbance (minor deviation, major deviation and failure). An example of this categorisation is presented in Table 3.2, Chapter 3.

b. *Sources of SC vulnerability* are characteristics of the SC or its environment that lead to the occurrence of unexpected events and as such, they are direct or indirect causes of disturbances (Section 3.3.2).

Vulnerability sources can be distinguished as internal, SC related or external, and they can be uncontrollable, or partially or completely controllable by SC managers. Our work considers food SCs, and therefore, within our classification, we identify vulnerability sources specific to the food SC. In total, we found 41 main vulnerability sources, and 17 of them usually contain specificities of food SCs (see Figure 3.2).

c. *Redesign strategies* can be defined as sets of strategic and tactical plans and operational actions that aim to reduce the vulnerability of SCs based on one or more redesign principles that make changes in elements of the *SC scenario* (Section 3.3.3).

Redesign strategies can be classified according to their aim: to prevent a disturbance or to reduce its impact on SC performances. Furthermore, we present a classification of these strategies according to the concept they belong to (preventive or impact reductive) and a classification of basic redesign principles in relation to the specific elements of a SC scenario (i.e. the managed system, managing system, information system and organisation structure). In total, we identified 14 redesign principles aimed at disturbance prevention (see Table 3.3) and 16 redesign principles aimed at impact reduction (see Table 3.4).

The operationalisation of the research framework in a specific case is based on the following steps, which also indicates the relationships between the different elements of the framework:

1) The description of the SC scenario, and the identification of KPIs;
2) The identification and characterisation of unexpected events and disturbances in processes that have an impact on performance robustness;
3) The assessment of performance robustness;
4) The identification of sources of vulnerability; and,
5) The identification of appropriate redesign principles and strategies.

The application of the framework to the case of a meat SC confirmed that by analysing the performance robustness of specific scenarios we can detect and typify disturbances. Furthermore, for each disturbance found, we identified a set of vulnerability sources that can represent a direct or indirect cause of the disturbance. Then, per vulnerability source a set of redesign principles and strategies could be identified to prevent the disturbance itself. If preventive strategies are too expensive or impossible to implement, we identified strategies that could be used to reduce the impact of disturbance regardless of its source.

Findings RQ3: Relations between contextual factors of food SCs and the use of disturbance management principles

The third research question is answered in Chapter 4. To answer the question we first reviewed the relevant literature and then conducted three exploratory case studies. Based on a cross-case analysis we extracted empirical findings.

Case study analysis confirms the theoretical indications that contextual factors (product, process, SC network and SC business environment) influence the application of disturbance management principles (DMPs). However, our findings indicate a difference with regard to which contextual factors are hard to change and therefore they determine selection of DMPs and which contextual factors are easier to change and therefore influence the application of DMPs. Our findings show that the SC actors alter the contextual characteristics of the process and SC network (*soft* contextual factors) due to requirements derived from the contextual characteristics of products and the business environment (*hard* contextual factors).

The most significant finding is that in order to maintain robust performances, both preventive and impact reductive DMPs are applied more often either a) to *processes*, to cope with the requirements imposed by product characteristics (see propositions Π.1 and Π.2 for preventive DMPs in Section 4.4.1) or b) to *SC network* to cope with requirements arising from SC business environment characteristics (see propositions Π.5 and Π.6 for impact reductive DMPs in Section 4.4.2).

With respect to the application of particular *preventive* DMPs, our findings show that the main preventive DMP applied to *processes* to cope with the requirements imposed by hard *product characteristics* is P1: *assurance and reliability systems*, while the main preventive DMP applied to *SC networks* to cope with the requirements imposed by hard *business environment* characteristics is P2: *proactive control, analysis and monitoring* (see propositions Π.3 and Π.4 for preventive DMPs in Section 4.4.1).

With respect to the application of particular *impact reductive* DMPs, our findings show that the main impact reductive DMPs applied to *SC networks* to cope with the requirements imposed by hard *business environment* characteristics are R4: *Responsiveness* and to a lesser extent R2: *Flexibility*, (see proposition Π.7 for impact reductive DMPs in Section 4.4.2). Also, our findings show that the impact reductive DMPs the least applied to *processes* and *SC networks* to cope with the requirements imposed by hard product and business environment characteristics are R1: *Redundancy* and R3: *Information visibility* (see proposition Π.8 for impact reductive DMPs in Section 4.4.2).

We present all propositions within the conceptual models that depict relationships between contextual factors through use of preventive (Figure 4.2) and impact reductive disturbance management principles (Figure 4.3).

Findings RQ 4: Assessment of the impact of disturbances in SC processes on the robustness of (food) SC performances

Chapter 5 answers the fourth research question. To answer this research question we conducted an extensive literature review on modelling approaches for analysing impact of disturbances to food SC performances and performance measures to assess food SC vulnerability.

The literature review shows that current vulnerability assessment methods are mathematically too complex, and in the same time need to be simplified for practical problems (e.g. *network models*, *stochastic optimisation models*), too expensive for implementation (e.g. *SC Event Management*) or to a certain extent subjective (e.g. *Failure Mode and Effect Analysis*). Therefore, new methods are needed (Kleindorfer and Saad, 2005; Wagner and Neshat, 2010). In Chapter 5 we propose a new method for vulnerability assessment called the VULA method, which is based on well-known techniques (such as simulation) applied in a specific procedure aimed to produce results in the form of specific *vulnerability performance indicators* (VPIs) and a *vulnerability index* (VI). The review showed that multiple VPIs are needed for a deeper understanding of SC vulnerability (Melnyk et al., 2009), i.e. to assess the level and type of vulnerability.

VPIs can be defined as indicators that show deviation in magnitude and time (in total, on average or at maximum) of performance value from robustness range (RR), i.e. tolerance specifications.

VI can be defined as the weighted sum of relevant VPIs for the selected SC scenario.

The VULA method (Vlajic et al., 2012b) comprises the following three steps:

1) First, the robustness range for a specific KPI is specified and historical data is used to assess the performances on VPIs.
2) Second, a number of scenarios are defined related to prominent disturbances. Using historical data, complemented with results from simulation studies, the VPIs are evaluated for each scenario. By scaling and weighting the different VPIs a *VI* is calculated, which quantifies the SC vulnerability. This *VI* may give a first insight into

whether action should be taken, but it gives no direction as to what kind of redesign strategies should be considered.

3) The third step offers guidance in selecting redesign strategies through a vulnerability profile and response matrix that indicates what kind of response and redesign strategy is most likely to reduce SC vulnerability.

The application of the VULA method to the case-based example shows, (1) values of VPI that indicate duration and magnitude of vulnerability per type of disturbance, (2) which disturbance results in the highest VPI values, (3) which disturbance results in the highest VI for the selected KPI, and as such needs immediate attention and response actions, and (5) what are the results of the application of various redesign strategies to manage priority disturbances.

6.2. Integrated findings into the research framework for design of robust SCs

Chapter 3 presented a research framework for designing robust (food) SC. In Chapter 4 and 5 we further developed our structured approach to assess and redesign SC scenarios. In this section we try to integrate all our findings into a single integrated framework. This framework is shown in Figure 6.2 and comprises the following steps:

Step 1. Describe the SC scenario and identify its specific contextual factors.

When conducting a vulnerability assessment, the first thing to do is describe and analyse the SC scenario. The SC scenario comprises all resources, infrastructures, inventories, control and planning systems, information systems and organisational structures on the level of the company (process view) and the SC network (network view). As our findings in Chapter 4 show, characteristics of the SC scenario are industry-dependent and its specificities can be described by contextual factors.

The importance of contextual factors lies in the fact that these contextual factors may create vulnerability sources, or influence control actions and therefore influence disturbance management. Contextual characteristics of the product and business environment (hard contextual characteristics) represent potential vulnerability sources and as such influence the selection of DMPs. Process and SC characteristics (soft contextual characteristics) represent the elements of the SC scenario that are affected by the use of the DMPs.

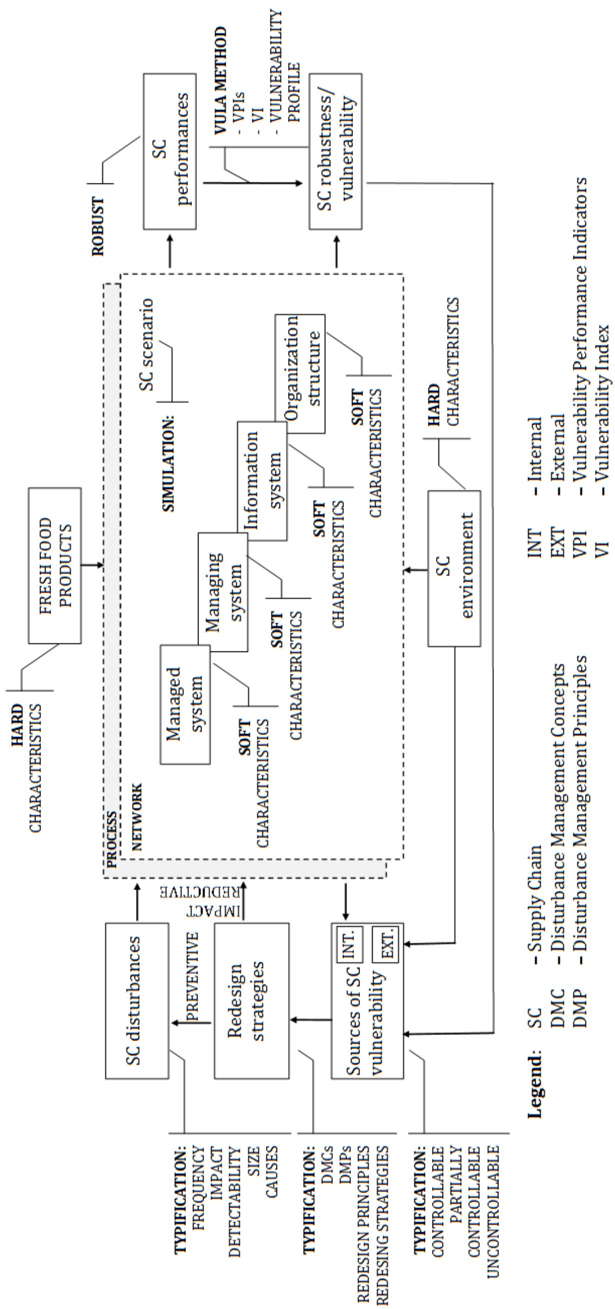


Figure 6. 2. Integrated research framework for designing robust (food) SCs.

Step 2. Identify potential types of disturbances that affect performances;

The second step is to analyse what unexpected events can take place in the SC that might affect the logistics performance. To make prioritisation of disturbances, each disturbance has to be characterised by the frequency of occurrence, the possibility of detection, the impact on SC performance.

As we show in Chapter 3, the cause and size of disturbances have to be analysed as well. To make a foundation for the identification of vulnerability sources and later use of redesign strategies, the causes of disturbances should be further analysed in a time, quantity and quality dimension, and size of disturbance can be ranked as a minor deviation, major deviation and failure.

Step 3. Define the relevant KPIs and identify the main disturbances by assessing the SC performance robustness

As our findings in Chapter 5 show, performance robustness can be assessed for any KPI by using the VULA method. The VULA method is applied to the results of the simulation model that is built to mimic the most important logistic features of the analysed system in normal working regime, as well as under disturbance in logistics processes. Outputs of the simulation model are values of the selected KPIs per different disturbance scenarios. These outputs are further used in a specific procedure aimed to produce results per scenario in the form of:

- specific VPIs, which show deviation in magnitude and time of performance value from robustness range (RR), i.e. tolerance specifications.
- a VI, which represents a weighted sum of relevant VPIs and indicates vulnerability level. The VI may give a first insight into whether redesign action should be taken.
- a vulnerability profile that indicates how much and how long performances are affected by disturbance, and a response matrix that indicates what kind of response and redesign strategy is most likely to reduce SC vulnerability.

Step 4. Identify the sources of vulnerability that may (strongly) affect the robustness of performance and eventually increase the vulnerability of the SC.

In this step the sources of vulnerability are determined for each of the main disturbances identified in step 3.

As we show in Chapter 3, external, SC related and company related vulnerability sources, should be further categorised according to their level of controllability. This classification is very important because it implies a direction for the use of disturbance management and redesign concepts: exposure of the SC to the more controllable vulnerability sources implies a reduction in the frequency of disturbances and exposure to the less controllable sources implies redesign which aims for a reduction in the impact of disturbances.

One of our principle findings from investigations in Chapter 4 is that contextual factors can create sources of vulnerability. From the aspect of controllability, product and SC environment characteristics are hard to change (we classify them as hard contextual characteristics) and therefore less controllable, while process and SN network are easier to change (we classify them as soft contextual characteristics) and therefore more controllable. Hard contextual characteristics influence the selection of disturbance management principles (DMPs), while soft contextual characteristics are affected by the use of the DMPs.

Step 5. Identify appropriate redesign strategies that eliminate disturbance by acting on sources of vulnerability or that reduce the impact of the disturbance by disabling the domino effect on other process and SC performances.

In this step relevant redesign strategies are determined. The redesign strategies belong to two Disturbance Management Concepts (DMCs): to prevent disturbances or to reduce their impact on SC performances.

As we show in Chapter 4, both concepts contain a set of DMPs that indicate what the objective is (e.g. to use proactive control, analysis and monitoring to prevent disturbances in the supply process) and a set of redesign principles that indicate how this objective can be met (e.g. by changing elements of Managing System within SC Scenario: control variability). Careful supplier selection process by using vendor rating techniques or the use of procedures and techniques to improve quality control are examples of particular redesign strategies that might be used preventively to manage particular disturbances in supply process considered in the analysis.

Step 6. Alter SC scenario elements that are affected by selected redesign strategies and repeat VULA method for KPI defined in Step 3

In the last step, to assess the effects of redesign the VULA method should again be applied to assess the effect of redesign. Based on repeated Step 3, VI indicates the vulnerability level after redesign, and vulnerability profile indicates whether a particular disturbance still affects the KPI and how. In principle, the less affected the KPI after redesign, the greater the effects of redesign have been, i.e. the more robust that KPI is and the less vulnerable SC is.

6.3. Theoretical relevance

This research has made the following contributions to the SCM literature.

Emerging research areas are identified

First, *we have identified emerging research areas* on robustness, and its counterpart vulnerability. From 2007 till now, a growing number of research papers that consider robustness have been published in academic literature in general, as well as in the SCM area (Figure 6.3). For example, in December 2007, 450,000 articles and books published on Google Scholar were considering robustness in some sense, and in April 2012 that number was more than double (922,000 articles and books). In 2007 in the Scirus database, SCM literature contained only around 35 relevant articles on robust SCs (Section 3 in Chapter 2), while in April 2012 that number is almost five times higher (163 articles). This is also confirmed by the recent literature review article on robustness (see Klibi et al., 2010) and other articles that are concerned with topologies, methods and strategies for design of robust SCs (e.g. work of Huaccho Huatuco et al., 2010; Salema et al., 2010; Urciuoli, 2010; Brintrup et al., 2011; Fujimoto, 2011; Peng et al., 2011; Schmitt and Singh, 2012; Stich et al., 2012). Klibi et al., (2010) confirm the existence of the research challenges we also identified: the need to incorporate vulnerability sources into SC analysis, the need to develop specific metrics and vulnerability index, but these authors also state the need to evaluate resilience and responsiveness of the chain as well as to consider the ecological footprint as important indicator.

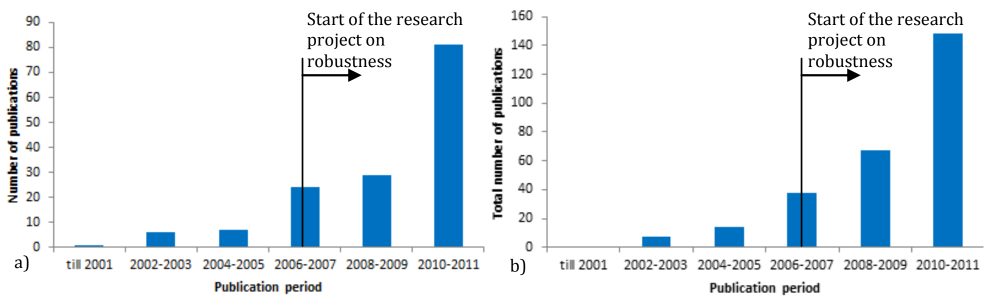


Figure 6. 3. Chronological overview of a robustness issues in reviewed publications in SC context per publication period (a) and cumulative (b) – Database Scirus, April 2012

Conceptual definition of supply chain robustness

Second we develop a *conceptual definition of SC robustness* that considers well defined scope and contains the main elements necessary for its further operationalisation (Chapter 3). Operationalisation of the definition in a illustrative case (Chapter 5) confirms its applicability, and moreover, it provide basis for assessment of the SC vulnerability level and vulnerability profile.

Integrated research framework

Third, we identified and structured the relevant elements for the design of robust SCs in the form of an *integrated research framework*. Application of the framework in a meat SC results in case-based identification and prioritisation of disturbances for selected KPI, as well as identification of corresponding vulnerability sources, appropriate redesign principles and potential redesign strategies. Moreover, we identified contextual factors and their characteristics which influence applicability of these redesign strategies for disturbance management. With this research framework, we contribute to a *better understanding* of the concepts of vulnerability and robustness and related issues in food SCs.

Importance of contextual factors on the use of disturbance management principles

Fourth, SCM literature implies a relationship between contextual factors and DMPs (Manuj and Mentzer, 2008), but there is no literature that explains this relation. Therefore, we identified contextual factors (based on the work of van der Vorst, 2000; Jüttner, 2005; Wagner and Bode, 2006; Lunning et al., 2011), and their characteristics for food SCs and found that they have a two-fold relationship with DMPs: products and SC environment are contextual factors that influence the selection and use of DMPs; processes and SCs are contextual factors that are influenced by DMPs. Moreover, we investigated dominant DMPs in fresh food SCs driven by large retailers.

A new vulnerability assessment method

Fifth, robustness of food SCs is an understudied but relevant area since food SCs have, in comparison to other SCs, a relatively high vulnerability level (Wagner and Neshat, 2010). In the fifth chapter, we contributed to SCM theory with the development of a new vulnerability assessment method. We defined SC *robustness* and developed *specific metrics for vulnerability assessment* (Vulnerability Performance Indicators -

VPIs), a *vulnerability profile* and a *vulnerability index*, which assembled together, form the basis of the new vulnerability assessment (VULA) method. In particular:

a) The value of our definition of SC robustness lay in its operationalisation and applicability to any KPI, either financial or logistic.
b) VULA method goes beyond comparing averages of some KPIs (which is a limitation of many previous studies) but also investigates different measures of variability of both the duration of impacts from disturbances and the fluctuations in magnitude. In particular, in food SCs this extension is crucial as fresh products flowing through a food SC are perishable and the companies involved must obey strict food safety restrictions (e.g. for freshness). We have illustrated the applicability of the method in a meat SC in which a simulation model was built to address the relevant features of these kinds of chains and to assess performances in different scenarios.

Finally, this whole project contributes to the SCM theory, and particularly to the new area focused on SC risk management (see Waters, 2007) with a systematic and comprehensive approach to the inter-related issues of SC robustness and vulnerability. Our findings and contributions are based on the use of different methodologies:

- literature reviews, which provided the foundation for definitions, categorisations and state of the art research,
- case study research, which provided empirical support for the developed framework and methods as well as formulated propositions,
- qualitative modelling, which enabled testing of the research framework for the design of robust SCs, and,
- quantitative modelling based on discrete event simulation and formulation of VPIs, which enabled vulnerability assessment of the focal company that belong to a particular type of SCs.

6.4. Research limitations and further research

This thesis provides a systematic and integral approach for the design of robust food SCs. However, there are certain research limitations that provide new challenges for future research:

a) Though the applicability of the research framework, developed in Chapter 3, is partly confirmed by testing it on the case of a meat SC, more research is needed to extend and validate our findings. First, more case studies could be done within the food industry to be able to construct generic overviews of sources of vulnerability and redesign strategies. Second, in order to select the most appropriate redesign strategies more research is needed to assess the impact of disturbances on key SC performance indicators (Klibi et al., 2010).

b) Empirical results from three case studies described in Chapter 4, indicate the type of influence between contextual factors and DMPs. However, to generalise the findings it is necessary to conduct more case studies for other types of food products (perishable and non-perishable), for other types of products and other types of SCs (where retailers are not the most powerful SC actor). This especially applies to the dominant use of DMPs for specific kinds of products and SC environments.

c) The VULA method developed in Chapter 5 has been successfully tested on a specific case. However, there are some issues concerning the method that merit further reflection.

    1. First of all, our definition of robustness is based on the correct estimation of a RR, i.e. thresholds defined by tolerance specification. However, we do not address details regarding the method of robustness range estimation. Though in practice estimation of robustness range is often based on an expert's decision, theory offers a six sigma approach, as well as optimisation models as possible tools. Therefore, there is a research opportunity related to finding the best method for estimating the robustness range for particular KPI.

    2. Second, the impact of a specific disturbance to SC performance in practice depends upon the specific characteristics and the design of the SC. Hence, the best redesign strategy depends upon those specific characteristics. It is therefore very difficult to define generic best redesign strategies related to specific disturbances, which is something that would further strengthen the tool.

    3. Third, although in our method the disturbance detection is automated and quantified, the weighting of the VPIs still requires expert judgement and is thus subjective. Maybe risk preference measures would indicate and drive the selection of MPIs and TPIs, as well as their weights. Future research may be

directed to the development of more VPIs as well as a more advanced method of determining weight factors in the vulnerability index. Additional measures, such as a conditional risk could be used as well (cf. Erkut and Verter, 1998). Also other statistical measures for disturbance detection and redesign improvement, such as kurtosis (e.g. Boger et al., 2001), could be useful.

4. Fourth, there should be enough historical information available in the company or SC to conduct the performance assessment. This will be overcome once more data is collected through applying the method. This again will result in more insight into disturbance frequencies and impacts as well as into the most important sources of vulnerability. It therefore becomes a learning system for the organisation resulting in more and more robust performances over time.

It is clear that additional research is needed to validate and extend our findings. More case studies can be done in the food industry to get more insight into the relationship between different kinds of disturbances and appropriate redesign strategies. Also, based on the fact that one company could be part of many SCs, defining the most appropriate KPI that would represent robustness of the entire SC is another research opportunity.

6.5. Managerial implications

With this project, we also hope to have delivered practical insights into food SC vulnerability. Based on all the literature reviews, we hoped to have helped to increase awareness in the professional SCM and logistics community about vulnerability and robustness issues. In particular:

a) The integrated framework and stepwise approach for the design of robust SCs can be used to guide food companies in managing disturbances and in designing robust SCs. From a practical point of view, managers of the meat processing company involved in the case study concluded that the research framework supports the analysis of the SC robustness and vulnerability, and helps in finding and categorising disturbances, vulnerability sources and appropriate redesign principles and strategies. The process of thinking about one's vulnerabilities in a structured way is a first step in redesigning a SC into a robust performing SC.

b) Empirical findings from case studies can help SC professionals in the fresh food industry to increase their understanding of the importance of "hard" characteristics of SCs for the creation of robust performing SCs. Moreover, an identification of "soft" characteristics of SCs and their categorization according to elements of the SC scenario can serve as a basis for assessing where to focus efforts to manage disturbance.

c) The VULA method we developed can help managers to assess the vulnerability levels of the company, identify how much the company would underperform in the case of a disturbance, how often would that happen and how long would it last, and ultimately give direction to what kind of response concepts to consider for each type of disturbance. The method studies SC vulnerability and would incite SC members to look more closely at their sources of vulnerability. In that way, top management gets more reliable information about the "health" of the company, which they can use to decide whether a process redesign is appropriate and what kind of redesign strategies to use in order to improve SC robustness. Moreover, the managers from the case company concluded that the VULA method contributed significantly to their understanding of their vulnerability, and helped them find relevant redesign strategies.

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Summary

The operation of supply chains (SCs) has for many years been dominated by a focus on efficiency, leanness and responsiveness. This has resulted in reduced slack in operations, compressed cycle times, increased productivity and minimised inventory levels along the SC. Combined with tight tolerance settings for the realisation of logistics and production processes, this has led to SC performances that are frequently not robust. SCs are becoming increasingly vulnerable to disturbances in their processes, which can decrease the competitive power of the entire chain in the market. Moreover, in the case of food SCs non-robust performances may ultimately result in empty shelves in grocery stores and supermarkets.

The overall objective of this research is to contribute to Supply Chain Management (SCM) theory by developing a structured approach to assess SC vulnerability, so that robust performances of food SCs can be assured. Furthermore, we aim to help companies in the food industry to evaluate their current state of vulnerability, and to improve their performance robustness through a better understanding of vulnerability issues. The following research questions stem from these objectives:

> *RQ1: What are the main research challenges related to (food) SC robustness?*
>
> *RQ2: What are the main elements that have to be considered in the design of robust SCs and what are the relationships between these elements?*
>
> *RQ3: What is the relationship between the contextual factors of food SCs and the use of disturbance management principles?*
>
> *RQ4: How to systematically assess the impact of disturbances in (food) SC processes on the robustness of (food) SC performances?*

To answer these research questions we used different methodologies, both qualitative and quantitative. For each question, we conducted a literature survey to identify gaps in existing research and define the state of the art of knowledge on the related topics. For the second and third research question, we conducted both exploration and

testing on selected case studies. Finally, to obtain more detailed answers to the fourth question, we used simulation modelling and scenario analysis for vulnerability assessment.

This structure of the rest of this summary is as follows. We begin by addressing the main findings related to the research questions. We subsequently show the contributions this research has made to the SCM literature and highlight important further challenges for future research. We finally recall the principal practical insights into reducing food SC vulnerability presented in this thesis.

Main findings

In Chapter 2 we address RQ1. To answer this research question, we first introduced our main motivation for researching the topic of SC robustness and vulnerability. After that, we explained our literature research method, i.e. identification of relevant articles from defined bibliographic databases and content analysis. Based on a detailed review of selected articles, we classified robustness definitions, identified the key elements used to define SC robustness, and identified the main research challenges for food SC robustness. The main research challenges were related to the need to define SC robustness more precisely, to identify and classify disturbances and their causes with reference to the specific characteristics of SCs and to make a systematic overview of (re)design strategies that may improve SC robustness. Also, we found that it is useful to be able to discriminate between varying degrees of SC vulnerability and to find a measure that quantifies the extent to which a company or SC shows robust performances when exposed to uncertainty and disturbances.

Chapter 3 is built on the main findings from the literature survey presented in Chapter 2. Hence, in chapter 3 we first define SC robustness and subsequently address RQ2.

> *SC robustness is the degree to which a SC shows an acceptable performance in (each of) its Key Performance Indicators (KPIs) during and after an unexpected event that caused a disturbance in one or more logistics processes.*

Based on the SCM literature we identified the main elements needed to achieve robust performances and structured them together to form a conceptual framework for the design of robust SCs. We then explained the logic of the framework and elaborate on each of its main elements: the SC scenario, SC disturbances, SC performance, sources of food SC vulnerability, and redesign principles and strategies. To verify the framework and explain the relationships between the elements, the research framework is tested via a meat SC case study.

In Chapter 4, we indicate a growing interest in both theory and practice for disturbance prevention and management and imply that the use of disturbance management principles (DMPs) is probably contextual. Numerous authors consider the following contextual factors to be relevant: products, processes, the SC network and the SC environment. To address RQ3 and explore the relationship between DMPs and contextual factors, we selected three fresh food SCs as case studies. In each case study we collected data on the relevant disturbances and contextual factors as well as the use of particular redesign strategies in relation to the contextual factors. Our major findings show that the contextual factors have a consistent relationship to DMPs. The product and SC environment characteristics are contextual factors that are hard to change and these characteristics initiate the use of specific DMPs as well as constrain the use of potential response actions. The process and the SC network characteristics are contextual factors that are easier to change, and they are affected by the use of the DMPs. We also found a notable relationship between the type of DMP likely to be used and the particular combination of contextual factors present in the observed system.

Modern SCs are highly effective and lean, but this increases their vulnerability, i.e. their susceptibility to disturbances reflected in non-robust SC performances. Both the SCM literature and SC professionals indicate the need for the development of SC vulnerability assessment tools. In Chapter 5 we addressed RQ4 by presenting a new method for vulnerability assessments, the VULA method. The VULA method helps to identify how much a company is underperforming on a specific Key Performance Indicator (KPI) in the case of a disturbance, how often this would happen and how long it would last. It ultimately informs the decision maker about whether process redesign is appropriate and what kind of redesign strategies should be used in order to increase the SC's robustness. The applicability of the VULA method is demonstrated in the context of a meat SC using discrete-event simulation to conduct the performance analysis. The case findings show that performance robustness can be assessed for any KPI using the VULA method. The VULA method is applied to the results of a simulation model, which gives output for the selected KPIs in each disturbance scenario. These outputs are used to produce results per scenario in the form of specific vulnerability performance indicators (VPIs). These indicators measure deviations in magnitudes and times from tolerance specifications; they also form the basis of our vulnerability index (VI), which represents a weighted sum of the relevant VPIs and indicates the vulnerability level. A vulnerability profile is then derived from the VPIs which indicates how much and for how long performances are affected by disturbances. This leads to a response matrix that indicates what kind of response and redesign strategy is most likely to reduce SC vulnerability.

In Chapter 6, we incorporated the findings of all previous chapters within an integrated framework for designing robust SCs. The integrated framework consists of the following steps: 1) Description of the SC scenario and identification of its specific contextual factors; 2) Identification of potential types of disturbances that may affect performances; 3) Definition of the relevant KPIs and identification of the main disturbances through assessment of the SC performance robustness (i.e. application of the VULA method); 4) Identification of the sources of vulnerability that may (strongly) affect the robustness of performances and eventually increase the vulnerability of the SC; 5) Identification of appropriate redesign strategies that eliminate disturbances by acting on the sources of vulnerability, or that reduce the impact of disturbances by disabling the domino effect on other processes and SC performances; 6) Alteration of SC scenario elements as required by the selected redesign strategies and repeat VULA method for KPIs, as defined in Step 3.

Contributions of this research

We believe this research has made a number of important contributions to the SCM literature. First of all, we have identified emerging research areas in robustness, and its counterpart, vulnerability. We have developed a definition of SC robustness, which contains the main elements necessary for its operationalization and also serves as a basis for the assessment of the extent of the SC's vulnerability and definition of the SC vulnerability profile.

Second, we identified and structured the relevant elements for the design of robust SCs in the form of an operationalized research framework. With this research framework, we contribute to a better understanding of the concepts of vulnerability and robustness and related issues in food SCs.

Third, we identified the relationship between contextual factors of food SCs and specific DMPs used to maintain robust SC performances: characteristics of the product and the SC environment influence the selection and use of DMPs; processes and SC networks are influenced by DMPs.

Fourth, we developed specific operationalized and applicable metrics for vulnerability assessments (VPIs), a vulnerability profile, and a Vulnerability Index, which together form the basis of a new vulnerability assessment (VULA) method. The VULA method goes beyond comparing averages of some KPIs and also investigates different measures of the variability of both the duration of impacts from disturbances and the fluctuations in their magnitude. This is needed in order to construct vulnerability profile that indicates how much and how long performances are affected by disturbance, and a response matrix that indicates what kind of response and redesign strategy is most likely to reduce SC vulnerability.

With this project, we also hope to have delivered practical insights into food SC vulnerability. First, the integrated framework for the design of robust SCs can be used to guide food companies in successful disturbance management. Second, empirical findings from case studies can help SC professionals in the fresh food industry to increase their understanding of the importance of contextual factors for the creation of robustly performing SCs. Moreover, the identification of changeable characteristics of SCs and their categorisation according to elements of the SC scenario can serve as a basis for assessing where to focus efforts to manage disturbances. Third, the VULA method can help top management to get more reliable information about the "health" of the company, and they can use it to decide whether a process redesign is appropriate, and what kind of redesign strategies to use in order to improve SC robustness.

Opportunities for future research

This thesis provides a systematic and integral approach to the design of robust food SCs. However, there are many challenges for future research that can now be apprehended. We mention here the two most important ones. First, there is a need to extend and validate our findings related to the research framework and contextual factors through further case studies related to other types of (food) products and other types of SCs. Second, there is a need to further develop and test the VULA method. This entails finding the best method for estimating the tolerance specifications for particular KPIs; defining generic best redesign strategies related to specific disturbances; to use other Vulnerability Performance Indicators (e.g. a conditional risk) and other statistical measures for disturbance detection and SC improvement (e.g. kurtosis); developing a more advanced method of determining the weight factors in the Vulnerability Index; and, finally, defining the most appropriate KPI to represent the robustness of a complete SC. We hope this thesis invites other researchers to pick up these challenges and help us further improve the robustness of (food) SCs.

Samenvatting

In de afgelopen twintig jaar hebben bedrijven in (logistieke) ketens zich vooral gericht op het creeren van efficiente, 'lean' en responsieve processen. Dit heeft geleid tot kortere cyclustijden, hogere productie- en leverfrequenties, hogere productiviteit en geminimaliseerde voorraadniveaus door de gehele keten. Het wegnemen van buffers uit de keten in combinatie met toegenomen prestatie eisen aan logistieke- en productieprocessen heeft geleid tot ketenprestaties die vaak niet robuust zijn. Bedrijven worden steeds kwetsbaarder voor verstoringen in hun processen, die de concurrentiekracht van de gehele keten in de markt kan aantasten. Zo kunnen niet-robuuste prestaties van voedselketens uiteindelijk leiden tot lege schappen in supermarkten en groentenwinkels.

Het doel van dit onderzoek is bij te dragen aan de Supply Chain Management (SCM) theorie door het ontwikkelen van een gestructureerde aanpak om de kwetsbaarheid van (logistieke) ketens te beoordelen, zodat robuuste prestaties van voedselketens kunnen worden gewaarborgd. We streven er naar om bedrijven in de voedingsmiddelenindustrie en -retail te helpen met het evalueren van hun huidige kwetsbaarheidsniveau, en om hun prestaties op het gebied van robuustheid te verbeteren. De volgende onderzoeksvragen komen voort uit deze doelstellingen:

1. *Wat zijn de belangrijkste onderzoeksuitdagingen met betrekking tot robuustheid van (voedsel)ketens?*
2. *Wat zijn de belangrijkste elementen die moeten worden beschouwd in het ontwerp van robuuste logistieke ketens en wat zijn de relaties tussen deze elementen?*
3. *Wat is de relatie tussen contextuele factoren in voedselketens en het gebruik van specifieke verstoringsmanagement principes?*
4. *Hoe kan het effect van verstoringen in logistieke processen op de robuustheid van (voedsel) ketenprestaties systematisch worden geanalyseerd?*

Om deze onderzoeksvragen te beantwoorden, zijn verschillende onderzoeksmethoden toegepast. Bij elke onderzoeksvraag hebben we een literatuuronderzoek uitgevoerd om tekortkomingen in bestaand onderzoek op te sporen en te bepalen wat de huidige stand van kennis is op het gebied van de daarmee verband houdende onderwerpen. Voor de tweede en derde onderzoeksvraag zijn zowel verkennend onderzoek als toetsing van bevindingen uitgevoerd in geselecteerde case studies. Tot slot hebben we simulatietechnieken en scenario-analyse gebruikt om een gedetailleerd antwoord te krijgen op de vierde vraag.

De structuur van deze samenvatting is als volgt. We beginnen met het bespreken van de belangrijkste bevindingen met betrekking tot de onderzoeksvragen. Vervolgens laten we zien welke bijdrage dit onderzoek heeft geleverd aan de SCM literatuur en geven we aanbevelingen voor toekomstig onderzoek. We eindigen met de belangrijkste praktische inzichten in het verminderen van kwetsbaarheid van voedselketens, die in dit proefschrift zijn gepresenteerd.

Belangrijkste bevindingen

In hoofdstuk 2 richten we ons op onderzoeksvraag 1. Om deze onderzoeksvraag te beantwoorden geven we eerst de belangrijkste motivatie voor dit onderzoek naar robuustheid en kwetsbaarheid in ketens. Daarna lichten we toe welke methodes we hebben gebruikt in ons literatuuronderzoek, dat wil zeggen hoe in bibliografische databases relevante artikelen zijn gevonden. Op basis van een gedetailleerde beoordeling van de geselecteerde artikelen hebben we definities voor robuustheid geclassificeerd, de belangrijkste elementen van ketenrobuustheid geïdentificeerd, en de belangrijkste uitdagingen voor onderzoek naar robuustheid van voedselketens op een rij gezet. Het onderzoek toonde aan dat de belangrijkste uitdagingen liggen in de noodzaak robuustheid van ketens exact te definiëren, relevante verstoringen te identificeren, oorzaken te classificeren aan de hand van specifieke ketenkenmerken, en het maken van een systematisch overzicht van (her)ontwerpstrategieën die de robuustheid van ketens kunnen verbeteren. Ook werd duidelijk dat het nuttig is om verschillende niveaus van ketenkwetsbaarheid te onderscheiden en om de mate waarin een bedrijf of keten blootgesteld wordt aan onzekerheid en verstoringen te kunnen kwantificeren.

Hoofdstuk 3 bouwt voort op de belangrijkste bevindingen uit de literatuurstudie gepresenteerd in hoofdstuk 2. Eerst definiëren we in hoofdstuk 3 ketenrobuustheid en vervolgens wordt onderzoeksvraag 2 behandeld. We hebben ketenrobuustheid als volgt gedefinieerd:

> *Ketenrobuustheid is de mate waarin een keten een acceptabele prestatie levert op (elk van) de Kritieke Prestatie Indicatoren (KPIs) tijdens en na een onverwachte gebeurtenis, die een verstoring in één of meerdere logistieke processen veroorzaakt heeft.*

Op basis van de SCM literatuur zijn de belangrijkste elementen nodig voor robuuste prestaties geïdentificeerd en gestructureerd bijeen gebracht in een conceptueel raamwerk voor het ontwerp van robuuste ketens. Daarna wordt de logica van het raamwerk en elk van de hoofdelementen toegelicht: het ketenscenario, verstoringen, ketenprestaties, bronnen van kwetsbaarheid van voedselketens, en principes en strategieën voor herontwerp. Om het raamwerk te controleren en uitleg te geven over de relaties tussen de elementen is het onderzoeksraamwerk getest in een case study in een vleesketen.

In hoofdstuk 4 laten we zien dat er, zowel in theorie als in praktijk, een groeiende belangstelling is voor preventie en beheer van verstoringen, wat impliceert dat het gebruik van verstorings-management principes (in het Engels Disturbance Management Principle, afgekort DMPs) waarschijnlijk contextueel bepaald wordt. Tal van auteurs achten de volgende contextuele factoren relevant: karakteristieken van producten, processen, ketennetwerk, en ketennetwerkomgeving. Om onderzoeksvraag 3 te beantwoorden en de relatie tussen contextuele factoren en DMPs te onderzoeken selecteerden we drie voedselketens met bederfelijke goederen als case studies. In elke case studie verzamelden we gegevens over relevante verstoringen en contextuele factoren alsmede het gebruik van specifieke herontwerpstrategieën. Onze belangrijkste bevindingen tonen aan dat de contextuele factoren een consistente relatie hebben met de DMPs. De karakteristieken van product en ketennetwerkomgeving zijn contextuele factoren die moeilijk te veranderen zijn en daarmee initiëren deze karakteristieken het gebruik van specifieke DMPs alsmede beperken ze het gebruik van potentiele DMPs. De specifieke karakteristieken van proces en ketennetwerk zijn contextuele factoren die relatief makkelijker zijn te veranderen. Tevens worden deze karakteristieken direct beïnvloed door het gebruik van de DMP's. Het onderzoek toonde ook aan dat bepaalde type DMPs voor de hand liggen ingezet te worden in de keten als er sprake is van een specifieke combinatie van contextuele factoren in het bestudeerde systeem.

Zoals eerder gesteld zijn moderne ketens zeer effectief en 'lean' ingericht, maar dit verhoogt hun kwetsbaarheid, dat wil zeggen hun gevoeligheid voor storingen die zich uit in niet-robuuste ketenprestaties. Zowel de SCM literatuur als ketenprofessionals wijzen op de noodzaak kwetsbaarheid assessment tools te ontwikkelen. In hoofdstuk 5 hebben we onderzoeksvraag 4 beantwoord middels de ontwikkeling van een dergelijke methode, de VULA methode. De VULA methode helpt te identificeren hoeveel een bedrijf slechter presteert op een specifieke KPI in het geval van een verstoring, hoe vaak dit zou gebeuren en hoe lang het zou duren. Uiteindelijk informeert het de beslisser of procesherontwerp passend is, en welke herontwerpstrategiën gebruikt moeten worden om de ketenrobuustheid te verbeteren. De toepasbaarheid van de VULA-methode wordt gedemonstreerd in een vleesketen, waarbij een discrete-event simulatie wordt gebruikt om de prestatie analyse uit te voeren. De bevindingen van deze case study laten zien dat met behulp van de VULA-methode de robuustheid in elke KPI kan worden bepaald. De VULA-methode wordt toegepast op de resultaten van een simulatiemodel, welke output geeft voor de geselecteerde KPI's in elk verstoringsscenario. Deze resultaten worden vervolgens gebruikt om per scenario resultaten te produceren in de vorm van specifieke prestatie-indicatoren voor kwetsbaarheid (in het Engels Vulnerability Performance Index, afgekort VPIs). Deze indicatoren meten afwijkingen van de tolerantie-specificaties ten aanzien van tijdsduur en grootte; Zij vormen ook de basis van onze kwetsbaarheid index (in het Engels Vulnerability Index, afgekort VI), die is opgebouwd uit een gewogen som van de relevante VPIs en inzicht geeft in het kwetsbaarheidsniveau. Een kwetsbaarheidsprofiel wordt afgeleid van de VPIs, die aangeven hoeveel en hoelang de prestaties worden beïnvloed door storingen. Dit leidt tot een zogenaamde response matrix die aangeeft wat voor soort response en herontwerp strategie het meest geschikt is om de ketenkwetsbaarheid te verminderen.

In hoofdstuk 6 worden tenslotte de bevindingen van alle voorgaande hoofdstukken samengevoegd in een integraal raamwerk voor robuust ontwerp van ketens. Het integraal raamwerk bestaat uit de volgende stappen: 1) Beschrijf het ketenscenario en identificeer specifieke contextuele factoren; 2) Identificeer potentiële soorten verstoringen, die (logistieke) prestaties kunnen beïnvloeden; 3) Bepaal de relevante KPIs en identificeer de belangrijkste verstoringen aan de hand van de VULA-methode; 4) Identificeer de kwetsbaarheidsbronnen, die de robuustheid van de prestaties (sterk) kunnen beïnvloeden en de kwetsbaarheid van de keten mogelijk kunnen verhogen; 5) Identificeer passende herontwerp strategieën, die verstoringen elimineren door invloed uit te oefenen op de kwetsbaarheidsbronnen of die de impact van verstoringen vermindert door het domino-effect op andere processen en ketenprestaties uit te schakelen; 6) Pas elementen van het ketenscenario aan zoals vereist door de geselecteerde herontwerp strategieën, en herhaal de VULA methode voor KPIs zoals gedefiniëerd in stap 3.

Bijdragen van dit onderzoek

Dit onderzoek heeft een aantal belangrijke bijdragen aan de SCM literatuur geleverd. Allereerst hebben we opkomende onderzoeksgebieden in robuustheid en zijn tegenhanger, kwetsbaarheid, geïdentificeerd. We hebben een definitie voor ketenrobuustheid opgesteld, die operationaliseerbaar is en die dient als basis voor de bepaling van de mate van ketenkwetsbaarheid en het ketenkwetsbaarheidsprofiel.

Ten tweede hebben we de relevante elementen voor het ontwerp van robuuste ketens geïdentificeerd en gestructureerd in de vorm van een operationeel onderzoeksraamwerk. Met dit onderzoeksraamwerk dragen we bij aan een beter begrip van de concepten kwetsbaarheid, robuustheid en aanverwante zaken in voedselketens.

Ten derde hebben wij de relatie tussen contextuele factoren van voedselketens en specifieke DMPs die worden gebruikt om robuuste ketenprestaties te behouden, geïdentificeerd: productkarakteristieken en de ketennetwerkomgeving beïnvloeden de keuze en het gebruik van de DMP's; processen en ketennetwerken worden beïnvloed door DMPs.

Ten vierde hebben we specifieke geoperationaliseerde en toepasbare dimensies ontwikkeld voor kwetsbaarheidsanalyses (VPIs), een kwetsbaarheidsprofiel en een kwetsbaarheidsindex, welke samen de basis vormen voor een nieuwe kwetsbaarheidsanalyse methode (de VULA methode). De VULA methode gaat verder dan het vergelijken van gemiddelde waardes van enkele KPIs; spreiding rond het gemiddelde wordt beschouwd door zowel de duur van verstoringen als de omvang van prestatieschommelingen mee te nemen in de analyse. Dit is nodig om een kwetsbaarheidsprofiel te bouwen dat inzicht geeft in hoe sterk en hoe lang een verstoring de prestaties beïnvloed, en een response matrix die inzicht geeft in de soort reactie en de herontwerp strategie die het meest waarschijnlijk is om de ketenkwetsbaarheid te verminderen.

We hopen met dit onderzoek praktisch inzicht te hebben verschaft in kwetsbaarheid van voedselketens. Ten eerste kan het integraal raamwerk voor ontwerp van robuuste ketens worden gebruikt om bedrijven in de voedselketen te begeleiden in het beheersen van verstoringen. Ten tweede kunnen empirische bevindingen uit case studies professionals in de voedselindustrie helpen het belang van contextuele factoren op het robuust opereren van ketens in te zien. Bovendien kan de identificatie van veranderlijke ketenkenmerken en hun indeling volgens de elementen van het ketenscenario dienen als basis voor het beoordelen van inspanningen die moeten worden gedaan om verstoringen te beheersen. Ten derde kan de VULA methode het topmanagement helpen om meer betrouwbare informatie over de "gezondheid" van het bedrijf te krijgen, ze kunnen dit gebruiken om te beslissen of een procesherontwerp nodig is, en om te bepalen wat voor soort herontwerpstrategieën gebruikt moeten worden om de ketenrobuustheid te verbeteren.

Aanbevelingen voor verder onderzoek

Dit proefschrift biedt een systematische en integrale aanpak voor het ontwerp van robuuste voedselketens. Er zijn echter nog veel uitdagingen voor toekomstig onderzoek. We noemen hier de twee belangrijkste. Ten eerste is er behoefte aan het valideren en uitbreiden van onze bevindingen met betrekking tot het onderzoeksraamwerk en de rol van de contextuele factoren door nieuwe case studies met andere soorten (voedsel)producten en andere typen ketens. Ten tweede moet de VULA methode verder ontwikkeld en getest worden. Dit omvat het vinden van de beste methode voor het schatten van de tolerantie specificaties van specifieke KPIs; het definiëren van generieke herontwerpstrategieën om specifieke verstoringen aan te pakken; het gebruik van andere kwetsbaarheid prestatie indicatoren (VPIs) (bijvoorbeeld, voorwaardelijk risico) en andere statistische methodes om verstoringen te detecteren en ketens te verbeteren (bijvoorbeeld op basis van kurtosis); het ontwikkelen van een geavanceerdere methode om wegingsfactoren te bepalen binnen de kwetsbaarheidsindex (VI), en, ten slotte, het definiëren van de meest geschikte KPI om de robuustheid van een volledige keten te bepalen. We hopen dat dit proefschrift ook andere onderzoekers uitnodigt deze uitdagingen op te pakken en ons te helpen verbetering van de robuustheid van (voedsel)ketens te realiseren.

About the author

Jelena V. Vlajic obtained a Bachelor degree and Master of Science degree at *Belgrade University*, the *Faculty of Transportation and Traffic Engineering, Logistic Department*. She worked at the faculty from 2000 until 2011 and as a research assistant and teaching assistant/junior lecturer she participated in several courses at bachelor and master level. The main ones were *Warehousing* and *Supply Chains*.

Since 2007, she has been enrolled as a Doctoral student in *the Logistics, Information and Decision Sciences Group*, *Wageningen University (WUR)*, the Netherlands. She attended courses at WUR, at the *European Institute for Advanced Studies in Management* (EIASM) in Brussels, and Doctoral MIT-Zaragoza Summer School in *Zaragoza Logistic Center*. Her doctoral project is related to a vulnerability analysis and the design of robust food supply chains. As a part of doctoral program, she participated as a lecturer for logistics courses at International MBA programs: "Agribusiness Innovation Management", at the *State Agricultural Academy Belgorod* (Russia) and *Kazan state agrarian university* (Russia), coordinated by WUR, and "International Agribusiness Management & Commerce" at the *Faculty of Agriculture, Belgrade University* (Serbia), funded by the Tempus project. She is the author and co-author of several peer-reviewed articles published in international journals and book chapters, as well as a reviewer for the international journals: *European Journal of Industrial Engineering* and *International Journal of Production Economics*. She participated in several research projects and she (co-)authored more than 20 scientific papers, 15 of them belong to the doctoral thesis:

1. Vlajic, J.V., van der Vorst, J.G.A.J., de Leeuw, S., (2012), "The use of disturbance management principles to decrease vulnerability in fresh food supply chains– empirical findings", in Vlajic, J.V., "Robust food supply chains, An integrated framework for vulnerability assessment and disturbance management", *PhD Thesis*, WUR, Ch. 4, pp. 70-109.
2. Vlajic, J.V., Lokven, S.W.M., Haijema, R., van der Vorst, J.G.A.J., (2012), "Using vulnerability performance indicators to attain food supply chain robustness", *Production Planning & Control: The Management of Operations*.
3. Vlajic, J.V., van der Vorst, J.G.A.J., Haijema, R., (2012), "A framework for designing robust food supply chains", *International Journal of Production Economics*, 137 (1), pp. 176-189.

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5. Vlajic, J.V., van der Vorst, J.G.A.J., Rijpkema, W.A., (2011), "Managing disturbances in supply chains of perishable food products - empirical findings", the *16th LRN Conference*, University of Southampton.
6. Vlajic, J., (2011), "Food supply chains in Serbia: how to increase competitiveness of domestic companies", invited lecture for the daily seminar Supply Chain Management – requirements for development and sustainability of companies in time of crisis, invited lecture - *Belgrade Chamber of Commerce*, 19. May 2011, Belgrade.
7. Vlajic, J.V., van der Vorst, J.G.A.J., Hendrix, E.M.T., (2010), "On robustness in food supply chain networks", in: "*Towards effective food chains*", Eds: Trienekens et al., Ch. 3, Wageningen Academic Publishers, pp. 63-82.
8. Vlajic, J.V., Haijema, R., van der Vorst, J.G.A.J., (2010), "Redesigning food supply chains to improve performance robustness using vulnerability profiling", the *15th LRN Conference*, Harrogate, pp. 668-678.
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10. Vlajic, J.V., van der Vorst, J.G.A.J., Haijema, R., (2009), "Framework for designing robust supply chains", the *14th ISL conference*, Istanbul, pp. 206-214.
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12. Vlajic, J.V., van der Vorst, J.G.A.J., Haijema, R., (2009), "Identifying sources of vulnerability and redesign strategies in the meat supply chain", the *14th LRN Conference*, Cardiff, pp. 947–951, (poster).
13. Vlajic, J.V., van der Vorst, J.G.A.J., Hendrix, E.M.T., (2008), "Achieving Robust Food Supply Chain Networks", the *15th International EurOMA Conference*, Groningen, pp. 1-10;
14. Vlajic, J.V., van der Vorst, J.G.A.J., Hendrix, E.M.T., (2008), "Food supply chain network robustness - A literature review and research agenda", *WICaNeM conference*, Wageningen, pp. 1–17;
15. Vlajic, J.V. (2008), "A modelling approach for designing robust international food logistics networks", in proceedings *7th EurOMA Doctoral Seminar*, Groningen University;

Participation in research projects:

1. "*A modelling approach for design of a robust food international logistic networks*", Wageningen University, (2007-2012).
2. Q-Porkchains, EU 6th Framework IP, "*Improving the quality of pork and pork products for the consumer: Development of innovative, integrated, and sustainable food production chains of high quality pork products matching consumer demands*", Module IV (2008).

Wageningen School
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Completed Training and Supervision Plan

Name of the activity	Department/Institute	Year	ECTS*
A) Project related competences			
Decision Science 2 (ORL-30306)	WUR	2007	6.0
EDEN doctoral seminar on research methodology in operations management	EIASM	2008	4.0
7th EurOMA Doctoral Seminar	EIASM	2008	3.0
Food Risk Analysis	WUR	2009	3.0
Research Methods of the Successful Scholar	ZLC	2010	0.4
Procter & Gamble: Insider's Lenses	ZLC	2010	0.5
Dynamic Programming with Applications	ZLC	2010	0.6
Supply Risk Management	ZLC	2010	0.2
Supply Chain Management	ZLC	2010	0.6
Mansholt PhD Day: Food supply chain network robustness - A literature review and research agenda	MG3S	2008	1.0
'Achieving robust food supply chain networks'	18th Euroma conference, Groningen	2008	1.0
'Framework for designing robust supply chains'	14th ISL conference, Istanbul	2009	1.0
'Assessing the vulnerability of food supply chains,	9th WICANEM conference, Wageningen,	2010	1.0
'Redesigning food supply chains to improve performance robustness using vulnerability profiling'	APMS conference, Cernobio	2010	1.0
'Redesigning food supply chains to improve performance robustness using vulnerability profiling'	LRN conference, Harrogate	2010	1.0
'Empirical study on food supply chain robustness and vulnerability – viewpoints of fresh produce processors'	APMS conference, Stavanger, NOR	2011	1.0
' Managing disturbances in supply chains of perishable food products – empirical findings,	LRN conference, Southampton, UK	2011	1.0
B) General research related competences			
Mansholt Introduction course	MG3S	2007	1.5
Techniques for Writing and Presenting a Scientific Paper	WGS	2007	1.2
Methods, techniques and computer tools for qualitative data collection and analysis	MG3S	2008	2.3
Scientific writing	WGS	2009	1.8
C) Career related competences/personal development			
Course – OR and Methods	Tempus project	2008	1.0
MSc Students supervision	ORL group	2008-2009	1.0
Member of Mansholt Phd Council	MG3S	2007–2009	1.0
Mobilising your scientific network	WUR	2010	1.0
Course: Logistics and Trading Nets	SAAB[a)]	2010	
Course: Logistics and Trading Nets	KSAU[b)]	2010	
Course: Logistics and Trading Nets	SAAB[a)]	2011	
Course: Logistics and Trading Nets	KSAU[b)]	2011	
Total (minimum 30 ECTS)			37.1

*One ECTS on average is equivalent to 28 hours of course work