WORKING PAPER
MANSHOLT GRADUATE SCHOOL

Food supply chain network robustness
- A literature review and research agenda -

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DISCUSSION PAPER No. 42
2008

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Abstract
Today's business environment is characterized by challenges of strong global competition where companies tend to achieve leanness and maximum responsiveness. However, lean supply chain networks (SCNs) become more vulnerable to all kind of disruptions. Food SCNs have to become ***robust,*** i.e. they should be able to continue to function in the event of disruption as well as in normal business environment. Current literature provides no explicit clarification related to robustness issue in food SCN context. This paper explores the meaning of SCN robustness and highlights further research directions.

Introduction
Today's business environment has become an international playing field in which companies have to excel in its logistical performance, i.e. markets require full responsiveness, high reliability of supply at the lowest cost. Therefore, Supply Chain Networks (SCN) have eliminated most non-value adding activities and have become leaner. As a consequence, the levels of uncertainty, dynamics and complexity increased in SCNs (cf Childerhouse and Towill, 2004; Prater, 2005) and they have become more vulnerable to unanticipated events (Dong, 2006).

Characteristics of SCNs are product and company specific (cf. Reiner and Trcka, 2004) - that implies that each SCN has a specific configuration, type of processes, resources, market, management strategies, standards, organization etc. In case of Food Supply Chain Networks (FSCNs), there are some additional characteristics that make these networks even more specific (van der Vorst at al, 2005):

- 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 time;
- Variability of product quality and supply quantity of farm-based inputs;
- High volume production systems and capital-intensive machinery;
- Specific requirements for logistic processes;
- Unpredictable consumer demands;
- Legislations concerning food production, distribution, trade, quality of products etc.

These specific characteristics of FSCNs lead to a further amplification of uncertainty, complexity and dynamics within these networks. Let us explain this in more detail.

Uncertainty is an inherent characteristic of SCN (Van Landeghem and Vanmaele, 2002). One of the key sources of uncertainty in the supply chain relates to the quantities, timings and specifications of end-customer demand (Stevenson and Spring, 2007). In other words, uncertainty within a FSCN can be seen as a characteristic of material, information and financial flow realization and from logistic standpoint it can be considered from different aspects, such as:

- *Time* (in the sense of duration of activity/process, starting or ending moment of activity realization, how often some activity/demand happen);
- *Quantity* (in the sense of supply, demand or physical transfer/modification of the goods);
- *Location/place* (in the sense where an activity starts/finishes);
- *Quality* (in the sense of quality of service or product);
- *Cost* (i.e. in the sense of fluctuation of currencies, but also in the sense where, when and why some additional cost may be generated).

If not properly managed/considered, uncertainty in SCNs can result in many forms of disturbances, such as ***deviation, disruption*** and ***disaster*** (Gaonkar and Viswanadham, 2006). Each of these forms has significant impact on the SCN design, resulting in a different network configuration and/or network planning and control system. Moreover, in that way uncertainty increases network complexity and dynamics too. Independently whether uncertainty is caused by internal factors (i.e. the FSCN design or specific characteristics of FSCN) or external factors, it reduces the predictability of control actions on system behavior (cf. van der Vorst, 2000). Therefore, uncertainty has a large impact on (F)SCN performance and causes ***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). Therefore, the ***dynamic*** character of SCNs is the result of constant change in their business environment (in one or more external factors). Moreover, the dynamic character of SCNs influence, and is influenced, by uncertainty within the network and SCN complexity.

Supply chains are ***complex*** networks (Christopher and Peck, 2004) and in general, SCN complexity is caused by the multiple interactions within the network itself (cf. Asbjørnslett and Rausand, 1999) and as stated, by the influence of external factors (cf. Peck, 2005). Moreover, according to Gribble (2001) as a system grows in complexity, small perturbations can result in large changes in behavior of the system (known as the butterfly effect). That effect can also be observed in SCNs, i.e. influence of different forms of disturbances on SCN performance. Complexity of a FSCN has a specific character due to an increased number of participants, interrelated product and process links, increased differences of participants' technical and technological level of development, specific standards and legislations concerning food preservation and quality, product characteristics, wider product assortment, consumer wishes for fresher and more natural products, smaller production lot sizes, and so on (cf. Perona and Miragliotta, 2004; van der Spiegel, 2004; Van der Vorst et al., 2005; Tang, 2006). As a system becomes sufficiently complex, unexpected perturbations and failure modes inevitably will emerge (Grible, 2001) – that means, complexity of SCNs influences SCN performance and causes SCN vulnerability.

According to Svensson (2000), ***vulnerability*** is defined as the existence of random disturbances that lead to deviations in the supply chain of components and materials from normal, expected or planned schedules or activities, all of which cause negative effects or consequences for the involved manufacturer and its sub-contractors. Supply chain ***vulnerability*** is an "ever-present but poorly understood fact of business life" (Haywood and Peck, 2003). According to Peck (2006a), "the vulnerability of the food chain is well recognized in the post 9/11 security environment, particularly in the US, where companies have been encouraged to adopt new measures to protect food supplies". From the logistics point of view, sources of the FSCN vulnerability (cf. Peck, 2006; Dong, 2006) are different kinds of deviations (usually regarding customer demands, but also regarding duration of logistic activities), disruptions and disasters (usually regarding supply of money, food, water, energy or fuel, system of communication or regarding climate causes).

Therefore, besides common goals in FSCNs such as cost minimization, customer service improvement and product quality preservation (van der Vorst at al., 2005a), factors as *increasing uncertainty, complexity and vulnerability* require FSCNs to become ***robust*** and ***flexible*** in order to maintain or improve their competitive position. A robust FSCN is desired because of its ability to continue to function in the event of disruption in some of its stages and in the same time flexibility is welcome, because the FSCN can adapt in a dynamic environment (cf. Dreo at al., 2006). Flexibility in the SCN is well studied. We refer to for instance the work of Garavelli, 2003; Barad and Sapir, 2003; Graves and Tomlin, 2003; Duclos at al. 2003; Gunasekaran at al., 2004; Surie and Wagner 2005; Slack, 2005, Stevenson and Spring, 2007, etc. On the other hand, there is no explicit clarification related to robustness issue in the (F)SCN context, and there is lack of insight in robustness on strategic, tactical and operational level - as far it is known to the authors of this paper. Therefore, our research objective is to provide a review of available literature on robust SCNs, explore the meaning of SCN robustness, with special attention to FSCN and highlight further research directions.

This paper is organized as follows. Section 2 describes our research method for the literature research and robustness issues investigation. Section 3 provides a general literature overview of the term robustness used in different disciplines and contexts. Section 4 discusses the main findings of our literature overview of approaches to robustness in the SCN context. Section 5 draws conclusions and outlines further research directions.

Research method

There is a wide and sometimes vague usage of the terms "robust" and "robustness" in scientific literature, resulting in numerous articles that contain these terms (e.g. 450.000 papers in Google Scholar). Additionally, these terms are sometimes used interchangeably with terms as "stability" or "reliability", and they are also often connected with the words "flexibility", "resilience" and "adaptability". This situation makes a literature research on this topic difficult and blurry. Therefore, in order to make a comprehensive literature research on robust (F)SCN, it was necessary to develop an adequate research method as a guide through the literature labyrinth.

Our research method is based on the choice of the most convenient bibliographic database, keywords and criteria for selecting relevant articles. 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 "Scirius" and Google Scholar are used for searching within text. Regardless of the type of document, the most relevant articles are selected. The keywords we used are: *robust, supply chain, network, design, modeling* and *strategy*. Searching is performed using a combination of these keywords. Research is constrained by timeframe of publishing - from 1980 up to today, although main articles from earlier period were also considered. Articles are collected at the beginning of year 2007, with constant updates of available articles until December 2007. Main criteria for article selection was definition or explanation what robust/robustness is in SCN context or possibility to translate the concept of robustness into the SCN context (in cases that the article belongs to another subject area). Special attention was paid to articles that are related to food industry and international SCNs.

In literature, the term "robust" is most frequently used in the context of design, but many articles can be found in the context of strategy, network and modeling (Figure 1). However, most of the articles found belong to the Engineering and Computer science subject area, where robustness is widely used without a well defined meaning or particular explanation. A relatively smaller number of articles can be found in supply chain management literature. In these types of articles, the term "robust" is mostly used in a combination with terms "design", "strategy" and "network", but mainly as adjective for other terms, such as: methodology, framework, understanding, process, results, technique, analysis, conditions etc. In the context of supply chain modeling, the term "robust" is the most often related to words such as: measure, optimization, solution and model. From 131 selected articles in the Scopus database, only 25 are found to be relevant (though, most of papers don't belong to SCM literature). Few other relevant articles, theses and books are found in searching within the text in Scirius database and Google Scholar. We found following:

1. Only 30 publications are relevant for research regarding robust SCN; two out of 30 publications refer to the agri-food area/food industry
2. Most of the relevant articles/publications are published in a last two years (Figure 2).

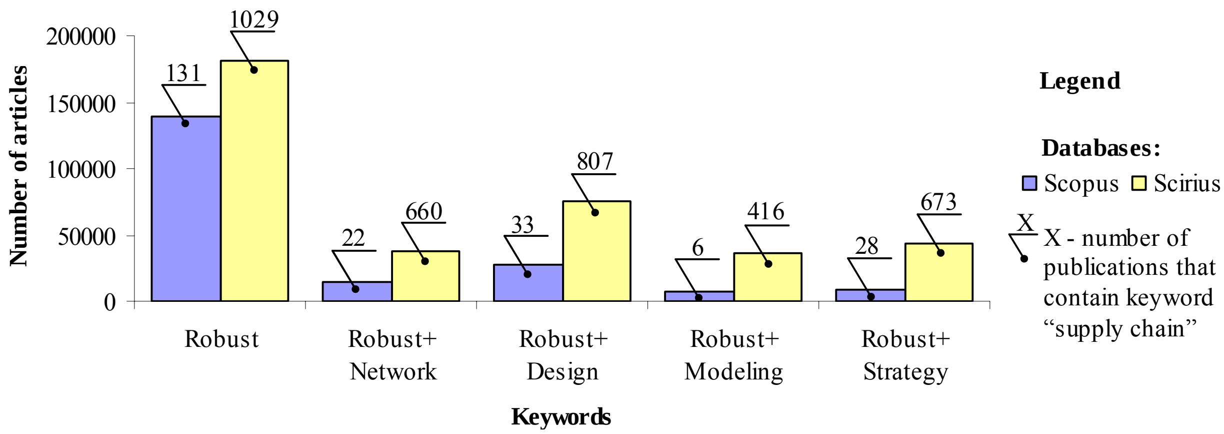

Figure 1. Number of articles that contain term "robust" and "supply chain" in combination with the given keyword(s).

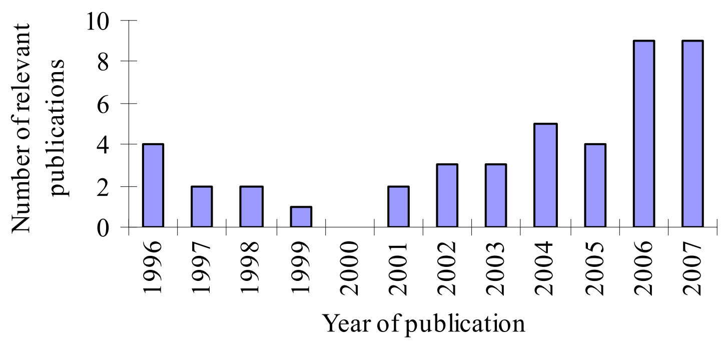

Figure 2. Chronological overview of relevant publications

What is Robustness?

The term robustness can be defined in many ways, depending on the specific context (Bundschuh at al., 2006). We found 42 definitions of robustness and typified them in few groups according to context, research direction or focus of authors (Figure 3). In next sections each of the defined groups is discussed shortly and in an overview of robustness definitions in SCN context is given. It has to be mentioned that some definitions belong to more than one group (i.e. work of de Neufville (2004) covers robustness from the aspect of strategy and desired property of the system, work of van Landeghem and Vanmaele (2002) covers robustness as a measure in context of supply chain planning, etc).

ROBUSTNESS AS		CONTEXT	AUTHORS
	MEASURE	statistics	Box and Jenkins (1976) - in Winkler, 1993
		optimization models	Gupta and Rosenhead (1968); Rosenhead, at al., (1972); Mulvey at al. (1995), *Snyder (2003);* List at al. (2003); *Wu (2006);* Leung at al. (2007) *Mudchanatongsuk at al., (2007);* Leung at al. (2007a)
		scheduling	Kutanoglu and Wu (2004); Herroelen and Leus (2004); Deblaere et al. (2007)
		planning	*Zapfel (1998); Van Landeghem and Vanmaele (2002);* Genin at al. (2007)
		general	Jen (2002)
		supply chain network or its part	*Goetschalckx, et al. (2001) – in Butler (2003); Tee and Rossetti (2002); Dong (2006); Dong and Chen (2007); Ouyang (2007)*
	METHOD and STRATEGY	decision making	Lempert at al. (2006); Groves and Lempert (2007)
		design	McCaskey and Tsui (1997); Gaury and Kleijnen (1998); De Neufville (2004);
		supply chain network	*Kleijnen (2005); Mo and Harrison (2005); Tang (2006, 2006a)*
	CHARACTERISTIC/ PROPERTY	system in general	Gribble (2001); de Neufville (2004)
		organization	Arndt and Müller-Christ (2005)
		scheduling	Jensen (2001); *Adhitya at al., (2007)*
		planning	Lasserre and Merce (1990); *Reiner and Trcka (2004)*
		supply chain network or its part	*Ferdows (1997); Asbjørnslett and Rausand (1999); Bundschuh at al. (2006); Chandra and Grabis (2007); Stevenson and Spring (2007)*

Figure 3. Typified definitions of robustness. Work that cover robustness in SCN context (directly or indirectly) is denoted in *italic letters*.

Robustness as a measure

The concept of robustness as a measure is introduced in Operations Research (OR) literature by Gupta and Rosenhead, (1968) and in Statistics literature by Box and Jenkins (1976) (in Winkler, 1993). Many of later definitions used in other scientific areas are based on these concepts. Appendix 1 provides an overview of the main definitions.

In *statistics*, robustness is related to the problem of internal consistency of the dataset and influence of contaminated data (data with extraneous large errors) on mean and standard deviation (Winkler, 1993). According to Winkler, mean and standard deviation "can be substantially different from the uncontaminated measures which are needed as a characterization of the process".

In *OR literature*, Gupta and Rosenhead (1968) developed a robustness concept for the problem of strategic investments (their work is extended in papers of Rosenhead at al., 1972 and Pye 1978). This concept is characterized by two components. The first component is based on examination of the optimal solution ("best end-state") and all other solutions close to the optimal one ("all end-states only slightly less advantageous"). Examination of solutions is performed using a so-called *robustness index* (see Appendix 1). The second component is based on requirement of stability. This requirement leads to criteria needed for robust solution selection out of many solutions with high robustness value. In this case, they refer to stable initial decisions – "decisions which create a system which, even in its incomplete state, will perform well". Since this concept makes sense for strategic decisions where risk, uncertainty and multiple objectives play an important role, it is used and adapted by many authors in other research areas.

A similar idea is used in the concept of *Robust Optimization* developed by Mulvey at al. (1995). This concept incorporates the conflicting objectives of solution and model robustness. Recently, the Robust Optimization concept is frequently used or adapted for different kinds of problems. Also, large number of models and robustness measures are developed and presented in a number of papers (see Appendix 1). Extensive review of robustness approaches in operations research literature, robust models and measures can be found in the doctoral thesis of Butler (2003).

Yet, some definitions of robustness as a measure are developed for specific problems and models and they cannot be categorized in previous groups – i.e. robustness in scheduling context (Kutanoglu and Wu 2004; Herroelen and Leus, 2004; Deblaere et al., 2007), planning context (Zapfel, 1998; Van Landeghem and Vanmaele, 2002). Some of definitions are given as a mixture of robustness as a measure and a concept of robust design (Genin at al., 2007) – more about robust design in next section) or they are given in general form (Jen, 2002) - see the definitions in Appendix 1.

Robustness as a method and strategy

The theoretical foundations of robust design have roots in techniques for planning and analyzing experiments developed by Fisher (1935) (in De Neufville, 2004). These techniques were well accepted in engineering, so robustness as a method has become well known in context of engineering design. *Robust design* is introduced by Taguchi in the 1980's, for the purpose of improving the fundamental function of the product or process to facilitate flexible designs and concurrent engineering. Robust design is based on the idea of selection of appropriate control factors and their settings so that the variance from the ideal value is minimal and all is achieved at low cost. Control factors represent in fact design factors that are controllable decisions affecting the process, and variance is the consequence of so-called "noise factors" (sources of variation) (cf. Mo and Harrison, 2005). Such a design is called a minimum sensitivity design (also called Taguchi method, experimental design or a robust design (www.isixsigma.com). Robust Design consists of Parameter Design (a systematic procedure for minimizing design sensitivity) and Tolerance Design (a process of balancing the cost).

Robust design has been constantly developed up to now (see e.g. McCaskey and Tsui, 1997; Gaury and Kleijnen, 1998; De Neufville, 2004 – see Table 1) and this idea is used in different research areas: in risk management (Gaury and Kleijnen, 1998), simulation (Schruben at al., 1992; Gaury and Kleijnen, 1998), SCM (Mo and Harrison, 2005), etc.

Table 1. Overview - definitions of robustness as a design method.

Definition of robust/robustness as:	*Authors*
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)

Robustness as *strategy* also emerged from the concept of Robust Design. Originally, the robustness strategy addressed ways for variance reduction and it provided the crucial methodology for systematic arrival at solutions that make designs less sensitive to various causes of variation. Today, robust strategy is used in much wider context. There are a lot of professional papers and commercial sites where "robust strategy" is used in context of planning, development, innovation and sustainability. However, there are only a few scientific papers that consider robustness as a strategy.

The work of Gribble (2001), De Neufville (2004), Lempert at al. (2006) and Groves and Lempert (2007) is interesting from the aspect of robust strategies. De Neufville (2004) for example identifies flexibility or robustness as "strategies to deal with uncertainty". However, considering the context of the article, robust strategy can be interpreted rather as one of the desired properties of the system (cf. Gribble, 2001) than strategy itself (see next section). In that sense, De Neufville (2004) proposed redundancy of parts as a strategy for achieving operational robustness in engineering systems. In the context of complex systems in computer science, Gribble (2001) proposed a few design strategies that can help a system to be robust: systematic overprovision (excessive capacity), admission control when system reaches saturate state, system introspection, adaptivity through closed control loops and plan for failure. Work of Lempert at al. (2006) and Groves and Lempert (2007) is based on the robustness concept of Gupta and Rosenhead, (1968), but with focus on strategies (much wider perspective than "options" in work of Gupta and Rosenhead, 1968). They implemented robust strategies for robust decision making under "deep uncertainty conditions"[1]. These authors defined *robust strategies* as strategies that perform relatively well, compared to the alternatives, across a wide range of plausible future states of the world. They also identified the most important properties of robust strategies in general: adaptability (they evolve over time in response to new information), they can serve as signposts and they can suggest type of actions that might be taken as response to signpost.

Robustness as a characteristic/property

In the proposed classification of robustness definitions, we also distinguish robustness as a characteristic/property of the given system. In the presence of complexity (cf. Gribble, 2001), uncertainty (cf. Lasserre and Merce, 1990; Gribble, 2001; de Neufville, 2004; Arndt and Müller-Christ, 2005) and vulnerability (cf. Gribble, 2001; Jensen, 2001; de Neufville, 2004), robustness is desired characteristic of the system (see Table 2).

Table 2. Overview - definitions of robustness as a characteristic/property in different contexts

Context	*Definition of robust/robustness as:*	*Authors*
System in general	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)
Organization	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)
Scheduling	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)
Planning	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)

Considering systems in general, according to Gribble (2001), a common goal that designers of complex systems strive for is robustness. Main reason for that goal emerged from unpredictable behavior of the system when it is faced with unexpected perturbations in an operating environment (see Table 2). In some systems (i.e. computer systems), the effects of small perturbations can result in global change (butterfly effect). A similar approach to this issue has de Neufville (2004), who proposes uncertainty management in engineering context using the time scale of response to uncertainty (divided into operational, tactical and strategic decisions) and type of response (to reduce the uncertainty itself, or to enable the system to respond to it better). In terms of enhancing the system, one can either strengthen it against a shock (to make it robust), or make it more flexible so that it can adjust to the shock.

A similar approach, achieving robustness at different levels of decision making is used in the context of planning and uncertainty (see definition of Lasserre and Merce, 1990 in Table 2, definitions of Zapfel, 1998 and Van Landeghem and Vanmaele, 2002 in Appendix 1). However, in the context of scheduling, robustness definitions are more related to some unexpected events/disruptions (Jensen, 2001).

Robustness in supply chain network context

In SCN literature, we found robustness defined as measure, method and strategy and property of SCN. In the selected papers, authors used one or more approaches to define robustness.

Robustness as a measure

The approach to robustness as a ***measure*** is mainly used for the problem of supply chain configuration design in presence of uncertainty (Goetschalckx, et al., 2001 – in Butler, 2003, Table 3) or major disruptions (Dong, 2006; Dong and Chen, 2007), Table 3. This problem belongs to the area of strategic network planning, and decisions made in this process have a major impact on the long-term profitability and competitive position of a corporation (Goetschalckx and Fleischmann, 2005). According to Dong and Chen (2007), extensive literature exists on the measurement of supply chain performance, but little of this work has focused on measuring supply chain's robustness, i.e., its ability to cope with deviation and disruption.

Table 3. Definitions of robustness as measure in supply chain network context

Definition of robust/robustness as:	*Authors*
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 supply chain 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 supply chain will avoid the bullwhip effect and all its deleterious economic consequences no matter what the customer does.	Ouyang (2007)

Goetschalckx, et al. (2001) – in Butler (2003) defined robust configuration of global supply chain using cost objective function and variability as a base for robustness measure (robustness index). The problem of the design of a supply chain configuration under data uncertainty and research directions are presented in Goetschalckx at al. (2002). In cases of variability of input data, SCN configuration models with robust solutions are developed and presented in Goetschalckx at al., 2004; Santoso at al., 2004; Goetschalckx and Fleischmann, 2005. However, in these papers, the focus in on financial performances and there is no description how to achieve a robust SCN configuration and what kind of performances should be used additionally. Dong (2006) presented an idea for quantifying the robustness index of the SCN networks, individual nodes and links after an event of major disruption. Although this idea gives a good insight in the state of a network after a disruption, this modeling approach considers a SCN as a static network with some deterministic characteristics, which is not appropriate for today's business environment and dynamic character of SCNs.

Other definitions of robustness in SCN literature are mainly based on the idea of robustness as a measure in optimization context, applied to strategic SCN issues, such as location problems (Snyder, 2003), supplier selection (Bundschuh at al., 2006) and tactical issues, such as production planning (Wu, 2006; Leung at al., 2007, 2007a), inventory management (Tee and Rossetti, 2002; Ouyang, 2007), fleet planning (List at al., 2003) etc. The core of these papers is often to find solution robustness and/or to analyze model robustness for a defined problem.

In reviewed publications, we have not found any publication where robustness is considered as a measure in the context of a FSCN. Yet, the issue of robust SCN design and modeling is a little bit tackled in the work of Wijnands and Ondersteijn (2006). These authors shortly presented advantages and disadvantages of robust modeling and results of a discussion about robust chains. Their major conclusion is that issues regarding robust modeling of agri-food SCN "are largely determined by inherent characteristics pertaining to agricultural production and food distribution". They point out that further research should therefore focus on incorporating the above issues in robust design of agri-food chains. Reiner and Trcka (2004) cover robustness from the viewpoint of solution robustness in the context of food supply chain simulation.

Robustness as a method and strategy

In SCM literature, only a few papers can be found on robust supply chain design (e.g. Mo and Harrison, 2005; Kleijnen, 2005) and robust strategies (e.g. Tang, 2006; Tang, 2006a); see Table 4.

Basic ideas about robust supply chain ***design*** have roots in the Taguchi method . Mo and Harrison (2005) used the following approach to determine a robust supply chain design under demand uncertainty: "find a set of design variables that provides the minimum deviation from a target value of the response when noise variables are considered at different levels". They used three OR methods to model a supply chain configuration that has the lowest total cost (or highest total profit) under all possible demand scenarios, and they developed several measures of its robustness. The proposed measures concern financial performances. However, one of these measures – "minimum total deviation from the firm's target value", can be used for other types of performances (i.e. lead time, service level etc). One of their main ideas is that an ideal robust supply chain design may have to consider more than one criterion, especially if we consider different levels of decision making. Kleijnen (2005) also used principles of the Taguchi's method to develop a methodology for searching for robust solutions in the context of supply chain simulation. He claims that in practice it is more important to find robust solutions than the optimal solution because robust solutions "give values for those factors that management can control, while accounting for the randomness of the environmental factors". Environmental factors are defined as non-controllable factors that create "noise". His paper does not mentioned what the environmental factors are that influence supply chain performances. Gaonkar and Viswanadham (2006) yet proposed a little bit different design approach. Their approach is based on risk management and introducing robustness into the supply chain at the planning stage. They focused on the design of robust supply chains at the strategic level through the selection of suppliers that minimize the variability of supply chain performance in terms of cost and output.

Additionally, they categorized risk problems according to uncertainty manifestations (expected and unexpected deviations, disruptions and disasters) and planning levels (strategic, tactical and operational). Similar to the approach of de Neufville (2004), they state that supply chains need to be robust at all three levels, strategic, tactical and operational and they provide some general directions towards achievement of that goal. Ismail and Sharifi (2006) proposed a new approach, "design for supply chain", inspired by the success of existing "design for X" techniques used in the area of Concurrent Engineering. In their design concept, processes are driven by market needs. That requires "the alignment of features to the basic strategic and operational supply chain properties of cost, quality and delivery and the extended properties of flexibility, robustness, innovativeness and service". Major point of their research, translated to the robustness issue is that robustness is a property of the SCN that should be considered during the design phase.

In SCM literature, supply chain ***strategies*** are a well known issue and they have different connotation from robust strategies that are described in previous text (see for instance the work of Tamas, 2000; Christopher and Towill, 2002; Frazelle, 2002 and Chopra and Meindl, 2007). However, recently some authors developed new approaches and introduced robust strategies for risk mitigating in the supply chain context (Simchi-Levi at al., 2002; Peck, 2005; Tang, 2006, 2006a). Robust strategies emerged from the recognition that more effective supply chains become more vulnerable to all kind of disruptions. Simchi-Levi at al. (2002) offered four SCN strategic approaches that can help the SCN to respond to generally unexpected major events and still to remain competitive. In general, they proposed the following strategies: Hedge Strategies, Flexible Strategies, Collaboration and Outsourcing. Peck (2005) generally mentioned strategies such as outsourcing and contract forms that should be used to mitigate supply chain risks and achieve supply chain resilience. Tang (2006, 2006a) stated that SCN resilience can be supported by implementation of robust SCN strategies (Table 4).

Table 4. Definitions of robustness as method and strategy in supply chain network context

Definition of robust/robustness as:	*Authors*
A robust supply chain design finds a supply chain configuration (or perhaps a group of supply chain configurations) that provides robust and attractive performance while considering many sources of uncertainty.	Mo and Harrison (2005)
A robust supply chain keeps its design fixed, and can still accommodate many changes in its environment.	Kleijnen (2005)
In order to motivate firms to secure their supply chains, "robust" strategies need to be developed that serve dual purposes. First, these strategies should be able to help a firm to reduce cost and/or improve customer satisfaction under normal circumstances. Second, the same strategies should enable a firm to sustain its operations during and after a major disruption.	Tang (2006) Tang (2006a)

Tang (2006) identified nine robust strategies that can be implemented under normal business circumstances or after major disruptions, and describes main challenges for strategy selection. In another paper (Tang, 2006a), those strategies are typified according to four SCM areas – supply management (multi-supplier strategy, revenue or risk sharing contracts), demand management (pricing strategy, demand postponement strategy), product management (product postponement strategy) and information management (strategies based on information sharing, VMI, or collaborative forecasting and replenishment planning). The most important properties of robust strategies are (Tang, 2006a): *efficiency* (the strategy would enable a firm to manage operational risks efficiently regardless of the occurrence of major disruptions) and *resiliency* (the strategy would enable a firm to sustain its operation during a major disruption and recover quickly after a major disruption). In an extensive literature review of quantitative models developed to analyze the influence of a particular strategy to supply chain performance, Tang (2006a) found that most of the quantitative models are designed for managing operational risks, and that there are not many papers in which the issue of disruption risks is addressed in an explicit manner. In the reviewed publications, we have not found any publication where robustness is considered as a method or strategy in the context of FSCNs.

Robustness as a characteristic/property

In the SCM literature, several publications can be found in which robustness is considered as a desired characteristic/property of a SCN. In the presence of complexity (cf. Asbjørnslett and Rausand, 1999; Reiner and Trcka, 2004; Adhitya at al., 2007; Chandra and Grabis, 2007), uncertainty (cf. Ferdows, 1997; Reiner and Trcka, 2004; Ouyang, 2007; Chandra and Grabis, 2007; Stevenson and Spring, 2007) and vulnerability (cf. Asbjørnslett and Rausand, 1999; Bundschuh at al., 2006; Adhitya at al., 2007; Chandra and Grabis, 2007), robustness is considered as a desirable characteristic of the SCN (see Table 5).

Considering globalization and uncertainty in the business environment, Ferdows (1997) introduced the "robust network" concept (Table 5). He connected robustness with security. From his point of view, security "is a necessary condition for cultivating the development of a site's competencies, which in turn allows the factory to expand its strategic role and its ability to deal with adverse conditions". A similar definition and approach to robust networks is presented by Stevenson and Spring (2007). However, their focus is supply chain flexibility, so the robustness issue is not investigated in more details. Robust planning under uncertainty conditions in a supply chain context is investigated in the work of Reiner and Trcka (2004). They provide a wide definition of a robust plan at strategic level. To guarantee a robust solution of the simulation model, they analyzed a food supply chain (pasta product) and estimated important parameters. Only Reiner and Trcka (2004) cover robustness from the aspect of measure and property in context of a FSCN.

Table 5. Overview - definitions of robustness in supply chain network context

Definition of robust/robustness as:	*Authors*
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. (supply chain context)	Reiner and Trcka (2004)
Ability of the supply chain to maintain a given level of output after a failure	Bundschuh at al. (2006)
The supply chain 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)
Dimension of supply chain flexibility, which represent "range of market change with which the existing supply chain configuration is able to cope"'	Stevenson and Spring (2007)
A robust system should be capable of handling both complete and partial rectifications (supply chain context)	Adhitya at al., (2007)

Asbjørnslett and Rausand (1999) considered robustness in the context of production systems. They introduced the vulnerability concept of production systems[2] and defined external and internal sources of vulnerability: different kind of disruptions and threats that affect the production system's business performances. A similar idea is used by Bundschuh at al. (2006) and Adhitya at al., (2007), but in the context of disruptions and their influence to SCN performances. Bundschuh at al. (2006) defined SCN robustness and its measures (number of supplier failures before a supply chain is completely disrupted and standard deviation of the performance's output) for several models. The developed models cover several situations and strategies used as a response to supply disruption. Their major finding was that the model with reliable and contingency supply shows the highest robustness. Adhitya at al., (2007) also defined robustness as desired property of the system in the case of disruptions. They proposed a model-based framework for rescheduling operations in the case of supply chain disruptions in a refinery supply example.

A mixture of ideas given by Ferdows (1997) and Asbjørnslett and Rausand (1999) is used in the work of Chandra and Grabis (2007). In their definition of robustness, they considered both: uncertainty in the business environment and disturbances that can affect SCN (similar to the definition of Tang (2006) and Tang (2006a) for defining robust strategies.

Conclusion and research agenda

Considering an extensive literature review and different kinds of approaches to the robustness issue , we draw the following conclusion regarding robust FSCN:

- Despite its frequent use, there is no general, widely accepted definition of robustness (Arndt and Müller-Christ, 2005). However, there are several approaches that can be used (one particular or combination) for developing a definition of FSCN robustness: robustness as a measure, method, strategy or desired characteristic/property of the SCN.
- In the presence of complexity, uncertainty and vulnerability robustness is a desired property of SCN in today business environment and it should be part of the SCN design process (cf. Gaonkar and Viswanadham, 2006; Ismail and Sharifi, 2006). For the purpose of design, three approaches can be used: the Taguchi method (Mo and Harrison, 2005; Kleijnen, 2005), risk management (Gaonkar and Viswanadham, 2006) and the "design for X" technique (Ismail and Sharifi, 2006).
- Several authors give their opinion or proposed definitions of robustness that should be valid in normal business circumstances, but also in cases of disruptions (Gaonkar and Viswanadham, 2006; Tang, 2006, 2006a; Chandra and Grabis, 2007). Additionally, robustness should be an overall measure of SCN competitiveness and more precisely related to certain business/key performance indicators (not only to a financial one). Considering different levels of decision making/planning and types of uncertainties/disruptions, the robustness definition should be valid at all three levels (operational, tactical, and strategic) and for all uncertainty manifestations/vulnerability sources (de Neufville, 2004; Gaonkar and Viswanadham, 2006).
- Although literature shows extensive work on the measurement of supply chain performance, little of this work has focused on measuring a supply chain robustness, i.e., its ability to cope with deviation and disruption (Snyder, 2003; Tang, 2006a; Dong and Chen, 2007). In available literature, we found several publications that cover the issue of robust supply chain configuration under uncertainty (Goetschalckx at al., 2002, Goetschalckx at al., 2004; Santoso at al., 2004; Goetschalckx and Fleischmann, 2005) and cases of disruptions (Snyder, 2003; Bundschuh at al., 2006; Dong, 2006; Dong and Chen, 2007). However, there are few papers that cover robustness issues at tactical and operational level (Van Landeghem and Vanmaele, 2002).

- Tang, (2006, 2006a) provided solid, general overview of robust strategies. However, there is open research direction related to questions: How to select an appropriate robust strategy for a particular SCN and when to implement that strategy, what should be the trigger for strategy implementation?
- There is no explicit definition related to the robustness issue in the FSCN context, as far it is known to the authors of this paper and there is a large research potential (cf Wijnands and Ondersteijn, 2006). Further research should therefore focus on defining FSCN robustness, incorporating the specific characteristics of FSCN into the design process and developing a suitable modeling approach for quantification of FSCN robustness.

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Footnotes

[1] "Conditions in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, or (3) how to value the desirability of alternative outcomes", Lempert at al. (2006)

[2] They defined production systems quite wide - it comprises humans, organizational and technical structures, as well as the interfaces and relations with the environment.

Appendix 1 - Overview - definitions of robustness as a measure in different contexts

Context	*Definition of robust/robustness as:*	*Authors*
Statistic	Robustness - a name for a class of statistics that are insensitive to large errors ("outliers")	Box and Jenkins (1976) - in Winkler, (1993)
Planning	Robustness index is "the ratio of number of expected external conditions which remain as open options to the number of good end-states considered."	Gupta and Rosenhead (1968)
	Robustness is a "measure of the flexibility which an initial decision of a plan maintains for achieving near-optimal states in conditions of uncertainty."	Rosenhead at al. (1972)
	At detail production planning level, a resolution of the demand uncertainty in context of production planning can be seen in a robust solution.	Zapfel (1998)
	At tactical level, a robust plan provides a "near-optimal" solution, which stays valid over a range of variable values at a predictable but higher cost and can be applicable for the sectors which are not able to achieve sufficient flexibility given their cost structure or because of technical limitations.	Van Landeghem and Vanmaele (2002)
	We qualify planning as being robust if and only if its characteristics show a weak dispersion in spite of the disruptive fluctuations of noise factors. Robustness is thus related to the dispersion of one or more performance measurements. Thus, a system can be robust, i.e. showing a weak dispersion of the measured functions, while being unstable: the manager changes systematically his decisions variables (instability) to reach the objective value (robustness).	Genin at al. (2007)
Optimization models	A solution to an optimization model is defined as: solution robust if it remains "close" to optimal for all scenarios of the input data, and model robust if it remains "almost" feasible for all data scenarios.	Mulvey at al. (1995)
	Robust optimization models are multi-objective models that trade expected performance off against some measure of ''risk'' based on how the system performs in the high consequence scenarios.	List at al. (2003)
	The goal of robust optimization in general is to find solutions that perform well under every realization of the uncertain parameters, though not necessarily optimally in any. The definition of "performing well" varies from application to application and choosing an appropriate measure of robustness is part of the modeling process.	Snyder (2003)
	"A robust optimization model with solution robustness means the solution will not differ substantially among different scenarios and there is less variability in the objective function across scenarios, which presumes a less aggressive management style." "A robust optimization model with model robustness means the violation of the some external constraints is permitted, but this is done by the least amount by introducing a penalty function."	Wu (2006)
	The optimal solution of a model will be robust with respect to optimality if it remains 'close' to optimality for any realization of the scenario.	Leung at al. (2007)

	The robust solution for an optimization problem under uncertainty is defined as the solution that has the best objective value in its worst case uncertainty scenario. Attractive features of a robust solution are that while it is only close to optimal for any specific scenario, it behaves well over all likely uncertainty outcomes.	Mudchanatongsuk at al., (2007)
	The optimal solution provided by a robust optimization model is called robust if it remains ‘‘close’’ to the optimal if input data change - this is regarded as solution robustness. A solution is called robust if it is ‘‘almost’’ feasible for small changes in the input data - this is regarded as model robustness.	Leung at al. (2007a)
Scheduling	A scheduling procedure or an algorithm is said to be more robust than an alternative if the schedules it generates achieve better performance (as defined by the objective function) under the same set of random disturbances and changes.	Kutanoglu and Wu (2004)
	The term quality robustness is used when referring to the insensitivity of the schedule performance in terms of the objective value. The term stability or solution robustness refers to the insensitivity of the activity start times to changes in the input data.	Herroelen and Leus (2004)
	Quality robustness is defined as the probability that a project ends within the project deadline. Solution robustness, also referred to as stability, is defined as a quality of the scheduling environment when there is little deviation between the baseline and the executed schedule.	Deblaere et al. (2007)
System generally	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 (2002)