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Methodology to evaluate the agility of a production network using a stress test approach

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AFFIDAVIT

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Graz, am (Matthias Schurig)

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Zusammenfassung

Das Ziel der vorliegenden Arbeit ist die Entwicklung einer Methodik zur Bewertung der Agilität von Produktionsnetzwerken. Dafür wird das Stresstest-Verfahren, bekannt aus der Finanzindustrie, auf die Umgebung der Produktionsplanung übertragen.

Produktionsunternehmen sind einem unsicheren und volatilen Umfeld ausgesetzt. Neben dem Flexibilitätkonzept bietet das Konzept der Agilität eine Möglichkeit, ihre Produktion auf diese Schwankungen einzustellen. Die in dieser Arbeit vorgestellte Agilitätsdefinition fokussiert auf die Anpassungsgeschwindigkeit sowie die wirtschaftliche Bewertung der Agilitätsalternativen. Zwar sind in der Literatur verschiedene Konzepte zu finden, wie Unternehmen ihre Wandelbarkeit bewerten können. Allerdings greift keines dieser Konzepte auf Stresstests zurück, die eine Bewertung der Wandelbarkeit anhand von historischen Stresstest-Szenarien ermöglichen. Die Übertragung dieses Vorgehens auf die Bewertung der Agilität von Produktionsnetzwerken steht daher im Mittelpunkt dieser Arbeit.

Die entwickelte Methodik besteht aus vier Schritten: Im ersten Schritt werden Zeiträume in der Vergangenheit identifiziert, die durch starke Nachfrageschwankungen charakterisiert sind. Diese Schwankungen werden in Stresstest-Szenarien für das zu bewertende Produktionsnetzwerk zusammengefasst. Dem folgt in einem zweiten Schritt die Erstellung einer Simulation des Produktionsnetzwerkes bestehend aus zwei Modellen: einem zur Materialflusssimulation und einem zur Gewinnsimulation. In Schritt drei wird mit Hilfe der zwei Modelle die Agilität von verschiedenen Produktionsnetzwerk-Konfigurationen simuliert. Das Ziel ist die Identifikation von Produktionsnetzwerk-Konfigurationen bestehend aus Agilitätsmaßnahmen mit verschiedenen Agilitätsniveaus. Abschließend werden die Ergebnisse der Agilitätsbewertung der untersuchten Produktionsnetzwerk-Konfigurationen dargestellt und ausgewertet.

Die vorgestellte Methodik ermöglicht die Bewertung der Agilität von Produktionsnetzwerken anhand von drei Kennzahlen: Größe der Kapazitätsflexibilität, Geschwindigkeit der Kapazitätsanpassung sowie der Profitabilität einer Produktionsnetzwerk-Konfiguration.

Die Validierung der entwickelten Methodik erfolgte durch die Anwendung in einem Produktionsnetzwerk eines europäischen Auftragsfertigers von Gesamtfahrzeugen. Es konnte gezeigt werden, dass die Agilität des Produktionsnetzwerkes in Bezug auf die verwendeten Stresstest-Szenarien insbesondere durch die Zulieferer beschränkt wird.

Abstract

The objective of this thesis is the development of a methodology to evaluate the agility of production networks. For that purpose the stress test approach known from the finance industry is transferred and applied in the production environment.

Production companies are facing an uncertain and volatile business environment. Besides flexibility, the agility concept provides the possibility to prepare their production for those fluctuations. The agility definition introduced in this thesis focuses on the speed of adaption as well as the profitability impact of different agility setups. The literature provides different concepts of how companies can evaluate their changeability. However, none of them uses the stress test approach to evaluate it by using historical scenarios. The transfer of this methodology to the evaluation of the production network agility is therefore the core of this thesis.

The developed methodology consists of four steps: Within the first historical time periods are identified characterized by strong demand fluctuations. These fluctuations are summarized in stress test scenarios for the production network in scope. Thereafter a simulation engine of the production network is created consisting of two models: a material flow and profitability model. Within the third step the agility of different production network setups using the simulation engine is evaluated. The objective is the identification of production network setups consisting of different agility measures with different agility levels. The final step demonstrates the results of the agility evaluation and are illustrated with insights being derived.

The methodology enables an agility evaluation along three KPIs: the capacity flexibility, speed of capacity adjustment and the profitability of production network setups. Additionally the relevance of suppliers for the agility of the production network can be evaluated and simulated.

The validation of the methodology was realized during an application at the production network of an European contract manufacturer of cars. It can be seen that the agility of the production network according to the stress test scenarios was limited by the suppliers.

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List of Abbreviations

ACEA	European Automobile Manufacturers' Association
BOT	Build-operate-transfer
CAGR	Compound annual growth rate
CEBS	Committee of European Banking Supervisors
CEO	Chief Executive Officer
COO	Chief Operating Officer
COGS	Cost of Goods Sold
DES	Discrete Event Simulation
EBA	European Banking Authority
EBIT	Earnings before interest and taxes
ERP	Enterprise-Resource-Planning
EUR	EURO
FMS	Flexible manufacturing system
IT	Information technology
JIS	Just in Sequence
JIT	Just in Time
KPI	Key Performance Indicator
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
ROI	Return on Investment
SG and A	Selling, General and Administrative Expenses
SME	Small and medium sized enterprises
SWOT	Strengths, Weaknesses, Opportunities and Threats
TQM	Total Quality Management
VoC	Volume-oriented Changeability
WIP	Work in progress

1 Introduction

1.1 Initial situation and motivation

Companies operating today are facing increasing volatility. Their environment is constantly changing and creates challenges: For example, economic downturns have Financial Crises as a consequence, expanding globalization leads to globally connected country risks, new technologies come up disrupting complete markets, young competitors attack established business models, just to name a few (Wildemann 2015*b*, pp. 14–35). Not only researchers, but also top managers such as Jeff Immelt (Chief Executive Officer (CEO) General Electric) or Norbert Reithofer (ex-CEO BMW) see volatility as “the new normal” (Fromm 2015), (Faber 2015).
Manufacturing companies perceive the high volatility and uncertainty in an accelerating rate. Drivers such as changes in demand patterns, rising factor input costs or effects of government policies trying to foster and support domestic manufacturing affect their business significantly (McKinsey 2012, p. 69). They recognize these changes by different factors such as increasing fluctuations of their received orders. Figure 1.1 illustrates the fluctuations of incoming orders of the German tooling machine industry between 1999 and 2009. The illustration shows strong order fluctuations of up to 50 per cent increases and down to 70 per cent decreases. Especially during macro-economic downturns, such as during a financial crisis orders vary significantly which creates operational challenges for companies.

The relevance of demand changes has increased over the past years (Nyhuis et al. 2008, pp. 70–71) and (Sheffi & Rice Jr. 2005, p.41). Whereas manufacturing companies prefer stability for their operation compared to long lead times, when the demand for their products is “far more dynamic” (Waller 2004, p. 18). Examples from the automotive industry show that sales forecasts done during the planning phase of a car production deviate up to 40 per cent in both directions compared to the final sales numbers occurred (Wemhöner 2006, p. 52).
However, by preparing their entire value chain, production companies can get ready to handle the volatility (Wildemann 2015*a*, p. 26). Abele & Reinhart (2011) observe that production companies need to adapt their production networks. Their production networks need to be both capable to “breath” as well as changeable to adjust to changes

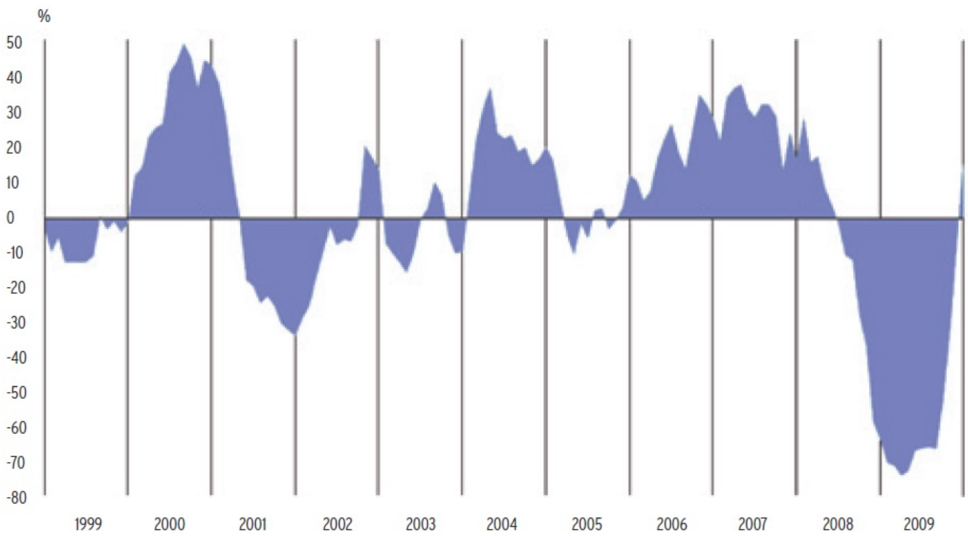

Figure 1.1: Order fluctuations of the German Tooling Machine Industry (Abele & Reinhart 2011, p. 175).

(Abele & Reinhart 2011, pp. 175–176). Wildemann (2015*a*) explains that supply chains also need to be ready to provide flexible capacities. Due to these fluctuations their production planning becomes more and more difficult for companies.

These few impressions demonstrate that companies are facing an increasingly changing world. As an effect, they need to prepare for changing settings. Different concepts are available empowering production companies to adjust to these challenges. Besides other concepts such as flexibility, agility is one concept permitting companies to prepare and react to changes. To use the full potential of agility, it is necessary to evaluate the current agility level of a production company. Currently there is no approach available how to assess the agility level of a company (Lin et al. 2006, p. 286). Furthermore, a concept is missing of how to financially evaluate agility and illustrate its benefits.

At the same time the stress test concept is used in the finance industry to assess the resilience of asset portfolios against unexpected events and changes (Fremdt & Völz 2010, p. 5). Henry et al. (2013, p. 6) state that financial stress tests aim to assess the stability of the banking sector against systemic risks. Assumed changes in risk factors which are "made large enough to impose some 'stress' on a portfolio" (Jones et al. 2004, p. 5). Jain & Leong (2005) transfer the approach to stress test supply chains, Wildemann (2015*a*) uses it to stress test business models of companies and the purchasing processes. Lange & Houston-Waesch (10.10.2015) describe how a stress test was built to assess the reserves of German utilities for the country's planned exit from nuclear power. The results were published in a report which assessed six scenarios (Warth & Klein Grant Thornton AG 2015). Transferring the stress test approach from these industries and application areas to the manufacturing industry has not been realized yet. The usage of the concept to assess the agility of a production system to react on changes can provide interesting new insights.

1.2 Objective of the research

The objective of this dissertation is to define a methodology to evaluate the agility of a production network. The stress test approach most currently used in the finance industry will be transferred to the application in production networks. Currently approaches to evaluate the changeability of a production are only available on a factory level. Examples are Klemke (2014), Wagner (2012) and Heger (2007).
The presented methodology contributes to the goal of companies to evaluate their agility level and adjust it to their needs. It should provide steps to evaluate the current level of agility and identify ways to adjust the agility level to the requirements defined by the management of the production network's leading company. By identifying an improved agility level, the production network will be able to react quicker on changes in their environment. The management of the companies which are part of the production network improves the capabilities of the production network to react on potential future uncertainties and volatility.
The methodology is limited to demand changes. Stressing demand scenarios need to be defined to test the agility of the production network. The methodology then enables the management of the production network to assess its agility referring to these stressful scenarios. This is done by defining production network setups consisting of different operational measures. These setups specify different agility levels including the current agility as well as improved agility levels.
The results of the agility evaluation support the management of the production network partners to regulate the production network agility. For that reason a quantitative assessment using operational Key Performance Indicators KPI is provided as a management support tool.

1.3 Research questions

Based on the objectives defined in the previous section, the following research question is derived:

> How can a methodology, inspired by the stress test approach most currently used in the financial industry, be designed to evaluate different production network setups regarding their agility?

To provide an answer to this main research question, sub-research questions have been derived:

1. What characteristics define agility?

2. How is agility in manufacturing defined and what characteristics need to be assessed for its evaluation?

3. How can the stress test methodology be adapted and transferred to the manufacturing industry aiming to evaluate the current and improved agility of a production network?

The main research question describes the overall objectives of the research effort. The goal is to provide a methodology to evaluate the agility of a production network. It is particularly interesting to use financial stress tests as an inspiration.
The three sub-research questions ensure a profound and structured way to an answer to the main research question. The first sub-research question aims to identify the agility characteristics which distinguish the agility concept from other changeability concepts such as flexibility and transformability. The identified characteristics are used as input for the agility definition in this thesis. The second sub-research question leads to a definition of agility in manufacturing which will be used throughout this thesis. The research question lays the basis for the concept which will be evaluated using the methodology. The sub-research question aims to understand which characteristics identified in sub-research question one are part of the concept. This sub-research question especially deals with how agility can be assessed quantitatively.
The third sub-research question investigates how the stress test approach most currently used in the finance industry can be transferred to the application in a production network. It is required to identify features of the finance stress test which can be transferred to the manufacturing environment. Additionally an explanation of how the stress test features need to be adjusted to be transmitted to the evaluation of production network agility is part of the answer.

1.4 Structure

This thesis aims to investigate and analyze a problem which is relevant in practice. The derived solution is a methodology which fulfills different requirements and is validated during an application in practice. Therefore, the applied research process is inspired by Ulrich (1981). According to his explanations the research is initiated by a practical problem. The available theory is used to explain the relations in practice. The research also ends in practice (Ulrich 1981, p. 19). His suggested seven step research process ensures that the solving of practical problems is realized by considering the relevant empirical research and builds on the required research focus. The process can be seen in (Ulrich 1981, p. 20).
For the thesis this means that a methodology will be developed which solves a practical problem. Relevant theory is used as input and delivers the required information. The

created methodology is than validated in practice and it is checked whether it solves the identified practical problem. Within the following section an outline of the thesis structure illustrated in figure 1.2 and inspired by Ulrich (1981) is given.

The second chapter introduces definitions of basic terms and concepts. Based on the delimitations and the research question evaluation characteristics are derived which ensure the newness of this research effort.

The third chapter discusses current research about stress tests as well as methodologies to evaluate the changeability of production. The available research is reviewed according to the evaluation characteristics. The identified research gap establishes the basis on which the remainder of the thesis relies upon.

Chapter four provides a conception of the developed methodology. Therefore basic definitions used throughout this thesis are introduced and compose the theoretical framework. Furthermore, the assumptions for the application of the methodology are specified. Chapter four closes with the description of the main idea of the methodology and an overview of the methodological steps.

The fifth chapter explains the four-step methodology in detail. To begin, reference time frames are identified to derive specific demand scenarios. In the next step two models are built-up: one to simulate the material flow within a production network and the second one to evaluate its profitability. The third methodological step evaluates different production network setups regarding their agility. Thereafter, step four illustrates the insights and the implementation of the selected measures.

The validation of the developed methodology is done within chapter six. The methodology was applied to a practical environment to evaluate the agility of a production network of an European contract manufacturer of cars.

Chapter seven summarizes the thesis. The answer of the research question is assessed by using the defined evaluation characteristics. Further the research results are critically reviewed and an outlook on further research topics is given.

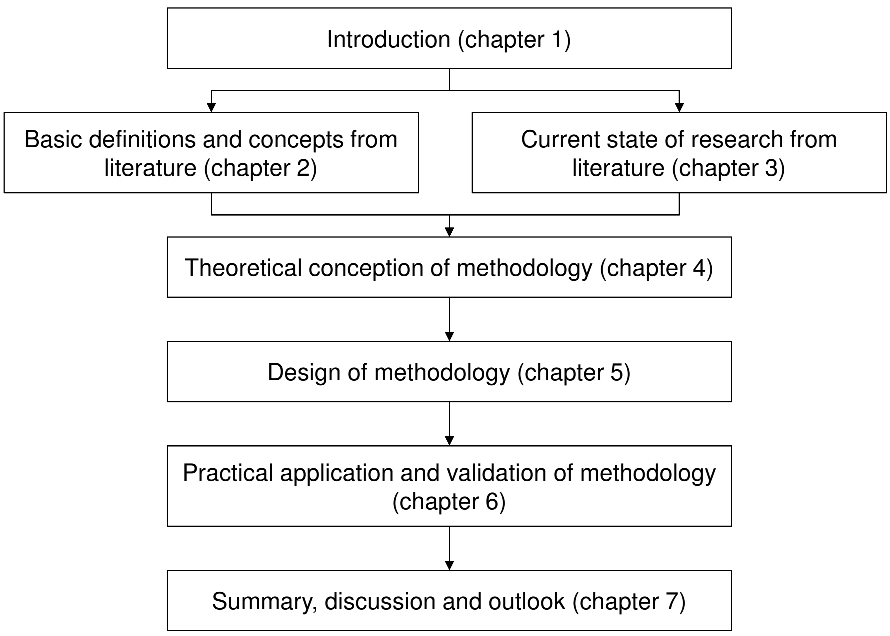

Figure 1.2: Structure of thesis, adapted from Ramsauer (2013, p. 12).

2 Definitions

To answer the research question and the corresponding sub-research questions a fundamental understanding of the terms used throughout this thesis is necessary. Therefore, they will be introduced and explained in this chapter. Moreover the terms are distinguished towards and compared with other available definitions and application areas. Based on the research question and these delimitations evaluation characteristics are derived which ensure the newness of the research effort.
Production, production networks as well as supply chain management are the fundamentals of this thesis. For that reason the definitions of these terms are provided in section 2.1. In section 2.2 different concepts of how manufacturing can react to changes are presented and discussed. Section 2.3 concludes the fundamentals by providing evaluation characteristics to secure the newness of the designed methodology.

2.1 Terms

In the following section, the terms 'production', 'production network' and 'supply chain management' are introduced, defined and discussed with respect to the research focus of the thesis. The objective of this section is to provide basic definitions to answer the research question specified in 1.3.

2.1.1 Production

An early definition of production[1] is provided by Gutenberg (1979, pp. 1–10). He defines the term 'production' as the combination of the elementary factors labor, material and machines by using the derivative factors planning and organization with the purpose of providing a service. The coordination and management of the elementary factors by the derivative factors is necessary to secure the successful provision of the required services. He emphasizes that besides the elementary factors a coordinating institution is necessary. A recent definition of Günther & Tempelmeier (2012, pp. 1–6) define production generally as a value creation process. The process combines simple or complex industry

[1] In the outline of this work production and manufacturing are used as synonyms

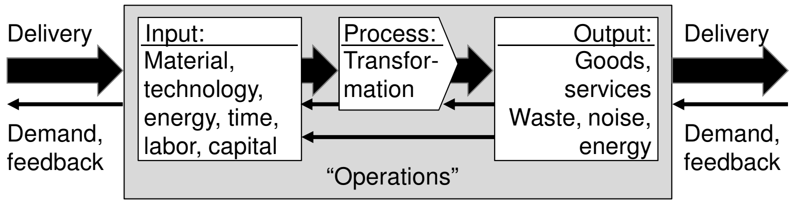

Figure 2.1: Illustration of a production process, translated from (Schönsleben 2011, p. 9).

goods and creates output goods which are upgraded in their value. They concretize the term by defining production as the creation of output goods (products) by using tangible and intangible inputs (production factors) on which specific technical operations are applied. Examples for tangible inputs are raw material or intermediate products. Intangible products are, for instance, licenses and patents. The authors describe the activity of production itself as a transformation process with the goal of a status change and value upgrade of the tangible products by using the production factors.
The two definitions of Gutenberg (1979) and Günther & Tempelmeier (2012) declare production as a process in which different factors are combined to increase the value of their inputs. Schönsleben (2011, p. 9) illustrates this process and its steps in figure 2.1.

Following Warnecke (1993, p. 1) production can be separated into two areas: the production of parts and their assembly. This means that the transformation process mentioned above can be separated into two succeeding steps: Starting with the manufacturing of different parts itself which are then assembled to a final product. This specification of the term production creates the prerequisite of separated production steps. It is the prerequisite to realize the production process at different places and also in different companies. It further establishes the foundation of production networks which are in the center of this thesis.
A production can be organized by the quantity of products it produces (Günther & Tempelmeier 2012, p. 4). Neumann (1996, p. 4) and Ramsauer (2009, pp. 9–36) mention the following types:

- Single piece production also known as make-to-order,
- Production of different product variants, called assemble-to-order,
- Batch production established as make-to-stock and
- Mass production.

This categorization structures the production types along how repeatable it be organized. Furthermore it shows how a production is set up according to the customer orders it fulfills. Whereas the single piece production is set up to fulfill very specific and unique

orders, the mass production is prepared to produce one product with a high repetition rate. These different setup types influence the way the production is organized and need to be taken into consideration when managing a production.
A further differentiation of particular production setups is categorized along its organization type. Neumann (1996, pp. 4–7) and Günther & Tempelmeier (2012, pp. 11–19) mention the following organization types of a production:

- Job-shop production,
- Line production,
- Flow production,
- Flexible manufacturing system and
- Manufacturing cells.

If similar functions are grouped in one space, the organization type is called job-shop production. Line production describes an identical material flow for all products without a timely connection. Flow production is set up for one material flow which is time-wise inter-connected. Flexible manufacturing system (FMS) and manufacturing cells connect different working systems and are capable of handling different material flows. A FMS describes an automated production connected with an automated material flow system. Manufacturing cells are not fully automatized (Günther & Tempelmeier 2012, pp. 11–19). These organization types are distinguished along how the material flows through their working stations.
Production takes place in a company and therefore Corsten & Gössinger (2012) define it as a subsystem of the company system. They define it as a production system (Corsten & Gössinger 2012, pp. 2–3).
Schuh & Schmidt (2014, pp. 3–4) correspondingly define a production system as a holistic organization concept in which the processes, the infrastructure and the environment of the production are included. Tools in form of production factors as well as concepts and methods are integrated. They state that a production system consists of two conceptually different, but closely connected layers: the execution layer where the transformation process of the production takes place and the management of the production on an overarching level. According to the authors the transformation processes do not have to be realized at the same production locations. This means that the production management as the higher instance level is responsible for the organization of the production at different production sites.
Nyhuis et al. (2008, p. 21) state that a production system can exist of one single production machine on the lowest level. The highest level of a production system can be formed by a production network consisting of different production sites. The production system is organized in a hierarchical way which means that higher levels always include lower

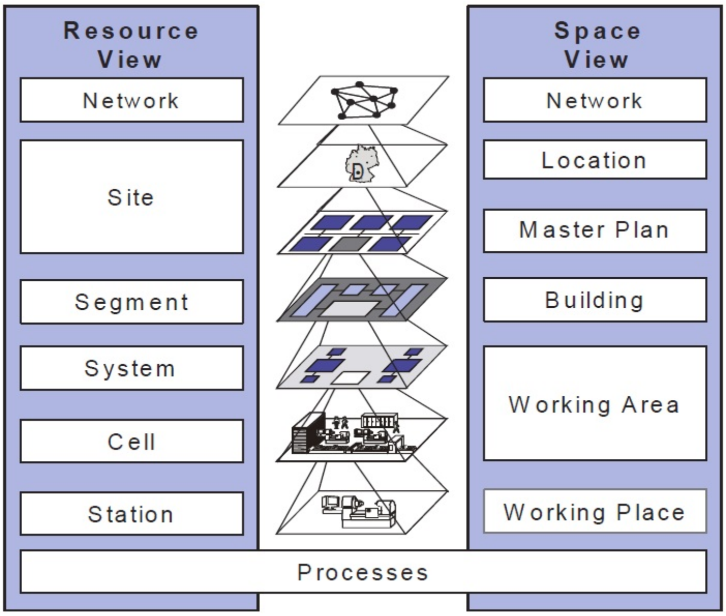

Figure 2.2: A production system (Wiendahl et al. 2007, p. 785).

ones. Moser (2014, p. 8) illustrates the structure of a production system in figure 2.2.

2.1.2 Production networks

Production networks enable the manufacturing of a product in different locations by using various partners. In the following, the term 'production network' is defined. The term 'network' is described from a theoretical point of view. It is then broken down into value adding network to finally derive production networks.

Networks in general

The term 'network' is broadly used, not only in management science, but also in fields such as Information technology (IT) or psychology (Moser 2014, p. 8). Kutschker & Schmid (2008, p. 532) provide a fundamental definition of the term network. They state that a network consists of nodes and edges. Nodes are defined as actuators of a network. Actuators can be an individual, a group, an organization or a nation. Edges are the direct or indirect connections, activities or interactions between the nodes.
In social sciences four types of networks are mentioned: networks of goods and services, information networks, networks of commonly shared values and norms and monetary networks (Albach 1993, pp. 27–28).
Sydow (2006, p. 1) concretizes the term network for management sciences. He defines a network in the area of companies as the cooperation in or between organizations, parts of organizations and companies. They exist relatively autonomous, yet are part of a net

of relationships. A network is therefore a counter model to deeply integrated companies. Companies cooperate closely in such networks to be able to react synonymously to turbulences within their environment. Creating networks provides the opportunity to share competences.
Sydow (2005, p. 79) categorizes company networks as a sub-group of networks. He defines them as an organization form of economic activities with the goal to realize competitive advantages. They are characterized by complex-reciprocal, more cooperative than competitive and relatively stable relationships between legally independent, but economically dependent companies. A company network has the goal to optimize the value adding chain. This is achieved by integrating economic activities across company boundaries. A company does not only rely on its own core competences. It uses available competences of partners and includes them into its own value-creation process. At the same time company networks imply an increased management complexity as the influence of the management is not limited to the company boarders. Furthermore, it requires an overarching network management to coordinate suppliers, partners and even competitors (Sydow 2005, p. 79).
Company networks can further be separated into inter- and intra-organizational networks. Whereas inter-organizational networks are characterized by long-term relations between two or more (usually legally) independent companies, intra-organizational networks are structures inside of one company (Kutschker & Schmid 2008, p. 536). Consequently networks do not exist only between different companies, but can also be initiated between different entities of one exclusive company.

Value adding networks

Value adding networks are a specific type of company networks. Every partner of the value adding network is responsible for a part of the value creation process (Schuh et al. 2011, pp. 476–477).
Stengel (1999, p. 1) defines value adding networks as a cooperative form of [at least] two companies which add value to a service or product in two consecutive steps. Their goal is to fulfill orders by combining suitable partners of a cooperation network ("order related cooperation"). The selection is done using market-oriented principles. Many different cooperations are possible, such as simple bilateral supplier relations, supply networks or the setup of joint ventures (Schuh et al. 2000, p. 69).
Companies are also collaborating in supply networks, another sub-form of value adding networks. Supply networks are described as vertically organized, hierarchical networks. Choi & Krause (2006, pp. 638–639) define supply networks as "all inter-connected companies that exist upstream to any one company in the value system". The supply base and the corresponding network are often coordinated and controlled by the focal company of a supply network. They define the supply base of a focal firm as "only those suppliers that

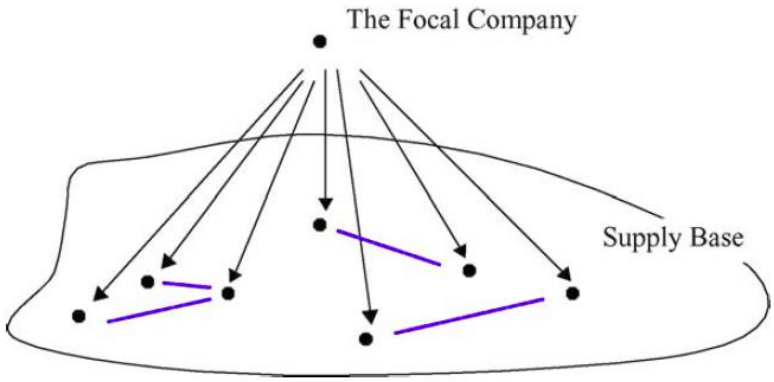

Fig. 1. Focal company and its supply base.

Figure 2.3: Relation between focal companies and supplier base (Choi & Krause 2006, p. 638).

are actively managed through contracts and the purchase of parts, materials and services [by the focal company]". Figure 2.3 illustrates the relations in a supply network.

Schindele (1996, pp. 110–111) identifies a shift of work content from manufacturers to suppliers, especially in the automotive industry. As the manufacturers, also named Original Equipment Manufacturer (OEM), want to limit the number of direct suppliers to reduce the management effort, the result is a supplier pyramid with different levels. Every level of this supply pyramid works with its direct suppliers. The focal company works directly with the first level (tier-1 suppliers) which are called system or module suppliers. The system suppliers work with the suppliers of the second level (tier-2 suppliers) which supply components. The suppliers on the third level (tier-3 suppliers) are called part suppliers.

Production networks

Sturgeon (2001, p. 11) defines production networks as "a set of inter-firm relationships that bind a group of firms into a larger economic unit". His definition shows that production networks are characterized by relationships between different firms collaborating to achieve an overarching goal.
Röhrs (2003, pp. 13–14) defines a production network as a network where nodes adopt subtasks of a production process and maintain service exchange relations (edges) via material and information flow. Stengel (1999, pp. 1–2) arrange production networks as a subgroup of value adding networks. He defines a production network as a value adding network where at least two companies are providing manufacturing services. Lutz & Wiendahl (2003, p. 685) add that cooperation in production networks is closer than in linear logistic and supply networks. The cooperation is limited regarding time, but nevertheless production networks are set up as long term cooperation. This is necessary as the intense cooperation between the companies need high investments which require a long

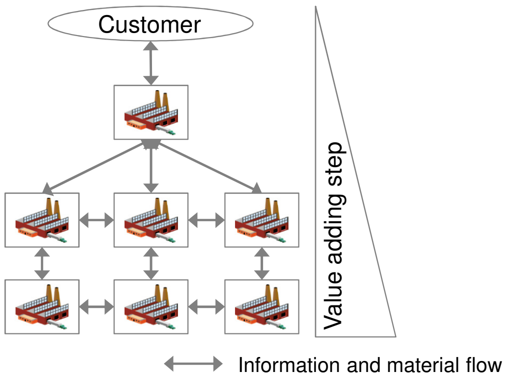

Figure 2.4: Structure of a production network, translated from (Lutz & Wiendahl 2003, p. 686).

time period to pay off. Furthermore, the communication within the production network is very high. A typical structure of a production network can be seen in illustration 2.4.

Different types of production networks are available. Eversheim et al. (2000, pp. 38–40) differentiate them along four criteria:

- Organization structure,
- Direction of cooperation,
- Realization type of cooperation and
- Type of the interfaces.

The organization structure is influenced by the duration of the cooperation. Whereas operational production networks are setup to cover capacity peaks by other locations, strategic networks aim to establish long-term relations among the network partners (Eversheim et al. 2000, pp. 38–40).
The direction of cooperation can be separated into vertical and horizontal dimensions. The vertical dimension encompasses the transfer of manufacturing content to suppliers. The horizontal dimension comprises the capability of global companies to produce the same product in different locations with the goal to realize location specific advantages and capacity smoothing effects (Friese 2008, pp. 7–8). Following Eversheim et al. (2000, pp. 38–40) the realization type of cooperation can be separated into the cooperation of production sites which are all part of one company or the cooperation between network partners of different companies. The type of interfaces describe the differentiation between an execution level and steering level in the production network. The categorization provides a structure how production networks can be set up and differentiated.
Lutz & Wiendahl (2003, pp. 686–687) state that production networks are closely related to supply chains. Their understanding of the relation between the two concepts is illustrated in figure 2.5. They distinguish the two concepts by the duration of the cooperation and

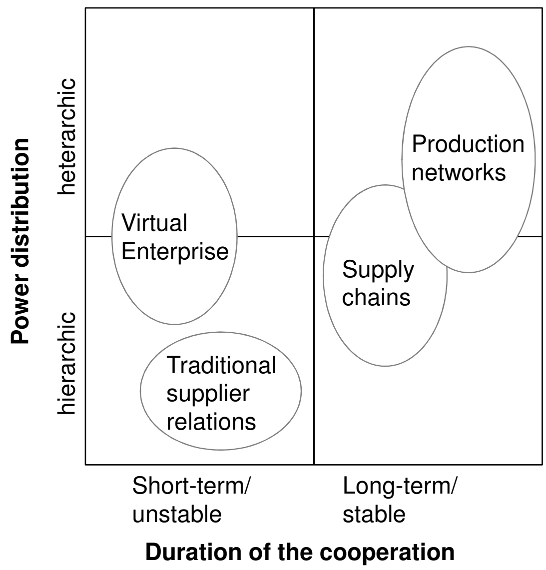

Figure 2.5: Classification of cooperation concepts in production, translated from (Lutz & Wiendahl 2003, p. 687).

the hierarchical level. The duration of the cooperation in production networks is longer than in supply chains. Additionally the cooperation between the network partners is more intense within production networks than in supply chains. This means that supply chains are organized in a more hierarchical method than production networks.

Lanza & Moser (2012, p. 257) argue that the importance of production networks increases with globally distributed locations. Their management gets more complex when the number of network partners constantly increases. Nevertheless the cooperation in production networks is an important way for big companies as well as for Small and medium sized enterprises (SME) to achieve competitive advantages.
Additional insights and definitions about value adding networks and production networks are provided by Röhrs (2003), Schuh et al. (2011) and Hensel (2007).

2.1.3 Supply chains

Many companies organize their supplier base in supply chains (Schuh, Hering & Brunner 2013, p. 2). Günther & Tempelmeier (2012, p. 9) explain that a supply chain aims to bridge the differences of distance, time and quantity between offer and demand. The whole chain includes suppliers, producers and customers. From their point of view a supply chain can be used as a synonym of supply networks mentioned in the previous chapter.
Stevens (1989, p. 3) defines supply chains more specifically as “the connected series of activities which is concerned with planning, coordinating and controlling material, parts and finished goods from suppliers to the customer”. His definition extends the view of

the supply chain from raw material until the customer. This is a more comprehensive perspective compared to production networks.
Simchi-Levi et al. (2008, p. 1) contribute elements of a supply chain. In their perspective it consists of “suppliers, manufacturing centers, warehouses, distribution centers, and retail outlets, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities”. Their view supports Stevens (1989)’s understanding that supply chain spans from raw material to the end customer.
Ben Naylor et al. (1999, p. 108) add in their definition of supply chains that the mentioned partners are “linked together via a feed forward flow of materials and feedback flow of information.”
The inclusion of the different partners mentioned above by Simchi-Levi et al. (2008) lead to a categorization of supply chains. Stadtler & Kilger (2005, p. 10) separates them into two types :

- Inter-organizational supply chains if external partners are involved and
- intra-organizational supply chains in a narrow sense if the supply chain consists of partners of the own company.

Stadtler & Kilger (2005, p. 15) state that “from the perspective of organizational theory, supply chains are a special form of a network organization. They consist of loosely coupled, independent actors with equal rights”. Gunasekaran et al. (2001, p. 71) point out that due to the increasing trend of integrating suppliers, for instance because of outsourcing trends, an active management of the supply chain is required to respond effectively to customer requirements within their view. Supply chains need to become lean and reduce costs. As a result, the integration and close management of these partners became necessary which resulted in the creation of supply chain management.
Supply chain management can be defined as “a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements“ (Simchi-Levi et al. 2008, p. 1). This definition shows that supply chain management tries to integrate and coordinate different partners across various legal entities. They are working to fulfill the requirements of customers. This also means that this definition includes the suppliers’ suppliers and customers’ customers in order to optimize the overarching performance of the system. It is not sufficient to only coordinate the production, transportation, and inventory decisions. Additionally, it is necessary to achieve an integration of the front end (the customer demand) to the back end (production and manufacturing) of the supply chain.
Whereas Simchi-Levi et al. (2008) use a goal-oriented definition of supply chain management, Wecker (2006, p. 24) provides a more process oriented definition. He defines supply

chain management as the integrated planning, organization, execution and controlling of the material and information flows of the network. The goal is to achieve an optimal design with respect to time, cost and quality requirements.
Another definition is provided by Stadtler & Kilger (2005, p. 11). They specify supply chain management as "the task of integrating organizational units along a supply chain and coordinating material, information and financial flows in order to fulfill (ultimate) customer demands with the aim of improving the competitiveness of a supply chain as a whole." The definitions of supply chain management underline that a systems thinking should be included. Bechtel & Jayaram (1997, p. 21) define systems thinking as the "movement away from functional department suboptimization of the supply chain to a holistic optimization of the entire supply chain. The focus in systems thinking is on how decision at a particular point in the chain affect the upstream and downstream points in the supply chain". Upstream in this context describes the material flow towards suppliers and their suppliers and downstream to customers and their customers (Schuh 2013, p. 24). The system thinking perspective shows that the members of a supply chain should be integrated and seen as a whole system. By doing so, local optimization is replaced by a thrive for global optimization which includes the entire chain.
In case the supply chain is not coordinated sufficiently, the so-called "bullwhip effect" may occur. It describes the effect that the demand fluctuations upstream in a supply chain are increasing drastically as the information between the partners flow slowly and are not always up-to-date (Jammernegg et al. 2000, p. 191). A great deal of research about the bullwhip effect was conducted, such as in (Alicke 2005, pp. 99–130).
According to Jammernegg et al. (2000, p. 200) there are four goals which a supply chain has to fulfill: delivering the right product, at the right time, at the right costs in the right quality. By measuring the fulfillment of these four goals the quality and performance of a supply chain can be evaluated.
Further research was done about supply chain, its management and its application in different industries. It can be referred to Stevens (1989), Simchi-Levi et al. (2008), Bretzke (2010), Klug (2010) and Schuh (2013).
To summarize it can be said that the supply chain of a company has the entire chain from the suppliers' suppliers up to the customers' customers in scope. This perspective delimitates it from production networks which only take the suppliers of a company and their suppliers into consideration. The perspective towards the end customers is not included.

2.1.4 Conclusion

In the previous sections the terms production, production network and supply chains were introduced and defined. In the further course the thesis focuses on production networks. The research effort refers to inter-organizational production networks consisting

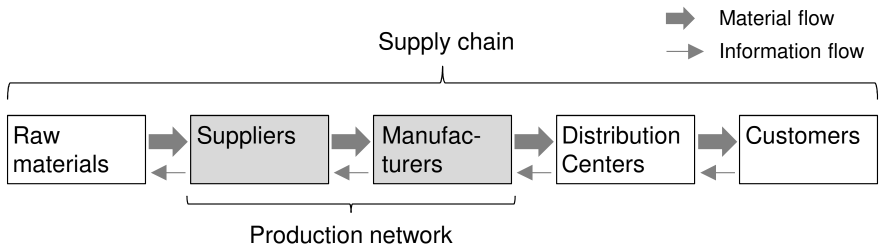

Figure 2.6: Relation between supply chains and production networks as used in this thesis.

of a focal company, specified as the OEM, and its suppliers. Different production sites of the OEM and the suppliers as well as technologies and transport relations are taken into consideration. All production network partners take over specific parts of the value adding process. Figure 2.6 illustrates the connection between production networks and supply chains used throughout this thesis.

2.2 Concepts to react on changes in production

Today's manufacturing environment is characterized by change. Globalization, dynamic markets with turbulences and uncertainties as well as the need for competitive advantages are main drivers affecting production companies (Schuh, Aghassi, Orilski, Schubert, Bambach, Freudenberg, Hinke & Schiffer 2013, p. 4), Ramsauer (2009).
Companies need to react to these turbulences and prepare themselves for the uncertainties. Production companies can react to these effects by improving their changeability (Wiendahl et al. 2007, pp. 783–785). Changeability in the outline of this thesis is used as a general term describing the ability of a production company to change. In literature different concepts of changeability are available. Within the following, the concepts flexibility, transformability and agility are discussed and defined. First insights about the differentiation of these changeability concepts were already published by the author in Schurig et al. (in review). This discussion and delimitation provides the basis for the introduction of an own definition of agility.

2.2.1 Flexibility

Flexibility is a concept which was discussed intensively in research in the past. That is why a lot of literature about different definitions of flexibility is available. This section aims to give an overview over different definitions of flexibility within manufacturing.
Various literature reviews about flexibility in manufacturing are available (Sethi & Sethi 1990, p. 289), Toni & Tonchia (1998), Beach et al. (2000), Koste & Malhotra (1999) and Gupta & Goyal (1989). Hence it is difficult to obtain a broadly accepted definition and

framework (Toni & Tonchia 1998, p. 1587).
Sethi & Sethi (1990, p. 295) provide a general definition of flexibility. They specify it as “the adaptability of a system to a wide range of possible environments that it may encounter. A flexible system must be capable of changing in order to deal with a changing environment”. Gupta & Goyal (1989, pp. 133–134) focus on the reaction of a system by defining flexibility as “a property of the system that indicates the system’s potential behavior, rather than its performance”. Upton (1994, p. 73) provides assessable characteristics of flexibility by defining it as “the ability to change or react with little penalty in time, effort, cost or performance”.
As this thesis focuses on flexibility in manufacturing, in the following two types of flexibility will be discussed in detail: Starting with a discussion around operational flexibility and followed by its integration in strategic flexibility.

Operational flexibility

Beginning with the work station level, Gupta (1993, p. 2950) defines machine flexibility as “the sum total of a machine’s ability to process a variety of different parts effectively”. This understanding of flexibility focuses on the processing of parts. The definition assumes that the more parts can be processed on a machine, the more flexible it is. It leaves an evaluation open how it can be achieved.
Gupta & Goyal (1989, p. 122) introduce an understanding of process flexibility that is based on economic consequences. They define process flexibility as “adaptability of the system to various changes in part processing, such as equipment and tool breakdowns”. He argues that poor performances in the processing of parts results in a higher Work in progress (WIP) level and hence higher costs of the parts produced. With this definition a direct connection between the process flexibility and its implied costs can be derived.
Browne et al. (1984, pp. 114–115) categorize flexibility for different operational levels especially for FMS. They identify eight types of flexibility outlined in table 2.1. These flexibility types span a broad range of abilities which a FMS can posses.

Not all of these flexibilities can be seen independently, but are connected with each other. According to Browne et al. (1984) an ideal FMS would possess all of the flexibilities outlined in table 2.1. Browne et al. (1984) indicate that an ideal FMS with all of the mentioned flexibility types would lead to high costs for the system. Therefore each company should select those flexibility types which it needs.
A further differentiation of flexibility in manufacturing is provided by Slack (2005, p. 1194). He separates flexibility into range and response flexibility. Range flexibility is characterized as “total envelope of capability or range of states which the production system or resource is capable of achieving”. Response flexibility focuses on the ease of responding in terms of cost and time, or both, and the change can be made within the capability enve-

Flexibility type	Definition
Machine flexibility	"Ease of making the changes required to produce a given set of part types."
Process flexibility	"Ability to produce a given set of part types, each possibly using different materials, in several ways."
Product flexibility	"Ability to changeover to produce a new (set of) product(s) very economically and quickly."
Routing flexibility	"Ability to handle breakdowns and to continue producing the given set of part types."
Volume flexibility	"Ability to operate a FMS profitably at different production volumes."
Expansion flexibility	"Capability of building a system, and expanding it as needed, easily and modularly."
Operation flexibility	"Ability to interchange the ordering of several operations for each part type."
Production flexibility	"Universe of part types that the FMS can produce."

Table 2.1: Flexibility types by Browne et al. (1984, pp. 114–115).

lope. This response enables to react on internal or external changes. Response flexibility is dynamically understood and focuses on short-term reactions. A combination of both flexibility subtypes supports the company's ability to react to changes.

Zelenović (2007, pp. 323–324) includes a time component into his flexibility definition. He defines the flexibility of a production system as "a measure of its capacity to adapt to changing environmental conditions and process requirements". He differentiates between the application and adaption flexibility. Application flexibility in this context means the degree of the usage of the installed capacity by the production system. Adaption flexibility describes the time the system needs to transform from one job to another. The inclusion of effectiveness and time into the flexibility concept by Zelenović (2007) is an important extension of the flexibility concept.

Nyhuis et al. (2008, p. 24) understand flexibility in a further way. They define it as the capability of a production system to adapt quickly and with low financial efforts to changing influence factors. These changes are described as achievable system states. They are predefined by a bundle of prepared measures and create defined flexibility corridors which are limited in their dimension.

The discussed definitions of operational flexibility describe how a manufacturing system is capable to react on changes. They explain how the system needs to adapt to be able to adjust a production to changes on an operational level. The early definitions of Browne et al. (1984) and Gupta (1993) focus on the way how the change can be realized. The definitions of Zelenović (2007) and Nyhuis et al. (2008) include a perspective of what is required to enable this change. They mention time and financial efforts that are required to realize the adjustment.

Strategic flexibility

Many authors such as Narain et al. (2000), Gerwin (1993) as well as Koste & Malhotra (1999) try to connect operational flexibility with strategic flexibility. Narain et al. (2000) provide a connection between operational and strategic flexibility in manufacturing. They separate into

- Necessary flexibility,
- Sufficient flexibility and
- Competitive flexibility.

All of the three types focus on different levels of a company, different times and problems. Necessary flexibility focuses on operational problems around the basic production factors, such as machine, labor or material handling. Sufficient flexibility focuses on tactical problems which deals with operations, production program or material. Competitive flexibility spans the connection to the strategy of a company by looking at the production, the expansion and the market (Narain et al. 2000, p. 206).
Gerwin (1993) follows in his definition closely the definitions of Slack (2005) by stating that in his view a production is more flexible than another "if it can handle a wider range of possibilities. It may be able, for example, to vary production through a greater range of volumes. A production system is also more flexible than another one if it can attain a new possibility in the range in a shorter period of time. While the cost of providing flexibility is sometimes used as a third aspect, here it is considered as part of the economic consequences" (Gerwin 1993, p. 398). The differentiation between range flexibility and response flexibility can be compared to Slack (2005)'s definition. From the perspective of Gerwin (1993) flexibility has to be seen as a multilevel framework connecting operational flexibility with the strategy of a firm. This connection is ensured with his proposed framework exposed in figure 2.7. The illustration shows how environmental uncertainties influence the manufacturing strategy of a company. From the manufacturing strategy the required manufacturing flexibility can be derived. The methods to deliver this flexibility are selected and can be influenced by the performance measurement. The performance measurement connects all of the elements and ensures an alignment of the delivered flexibility with the manufacturing strategy.

Koste & Malhotra (1999) suggest a hierarchy to connect the operational flexibility with the strategic flexibility on a business unit level. They provide a framework which shows the types of flexibility allocated to different organizational levels of a manufacturing company. They point out that, based on their research the different operational flexibilities are building blocks for the overarching strategic flexibility. Figure 2.8 highlights their framework.

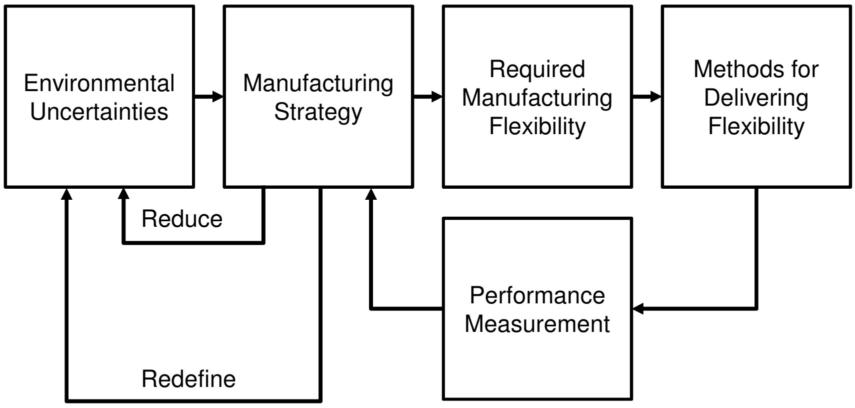

Figure 2.7: Conceptional framework to connect flexibility and a firm's strategy (Gerwin 1993, p. 398).

Based on the discussion above it could be shown that flexibility is one type of changeability. Flexibility enables a production company to react on changes on operational and strategic levels of a company. Concrete methods and measures how to achieve flexibility are not part of the discussion. It is described on a conceptual level. It becomes clear that flexibility describes an intrinsic capability of a manufacturing system to react on changes. Proactive preparation as well as an overarching financial perspective are not part of the concept.

2.2.2 Transformability

Another changeability concept to react to changes in production is known as transformability[2]. Transformability is a concept mainly developed and discussed by German researchers.

Westkämper (1999) provides an early definition of transformability. He describes a production system as transformable if its processes, structures and characteristics contain variability. All of its elements should be changeable. This makes the production system capable of reacting to changes in a reactive and anticipatory manner. The change should be realized under time constraints. The elements of the production system have to be adjustable to changing economic situations, for example, new order situations (Westkämper 1999, pp. 131–133).

Hernandez (2003) characterizes transformability in a more specific way. He defines it as a factory's potential to re-actively or proactively realize a determined reconfiguration of its elements by using change enablers inherent in the system and structure (Hernandez 2003, p.52). He sets the factory as the system boundary of the concept. Further researchers such as Scholz-Reiter et al. (2011, p. 6), Klemke (2014, p. 39) and ElMaraghy & Wiendahl

[2] In German discussed as "Wandlungsfähigkeit"; is also translated into English as "adaptability" or "changeability", in the following the translation 'transformability' is used

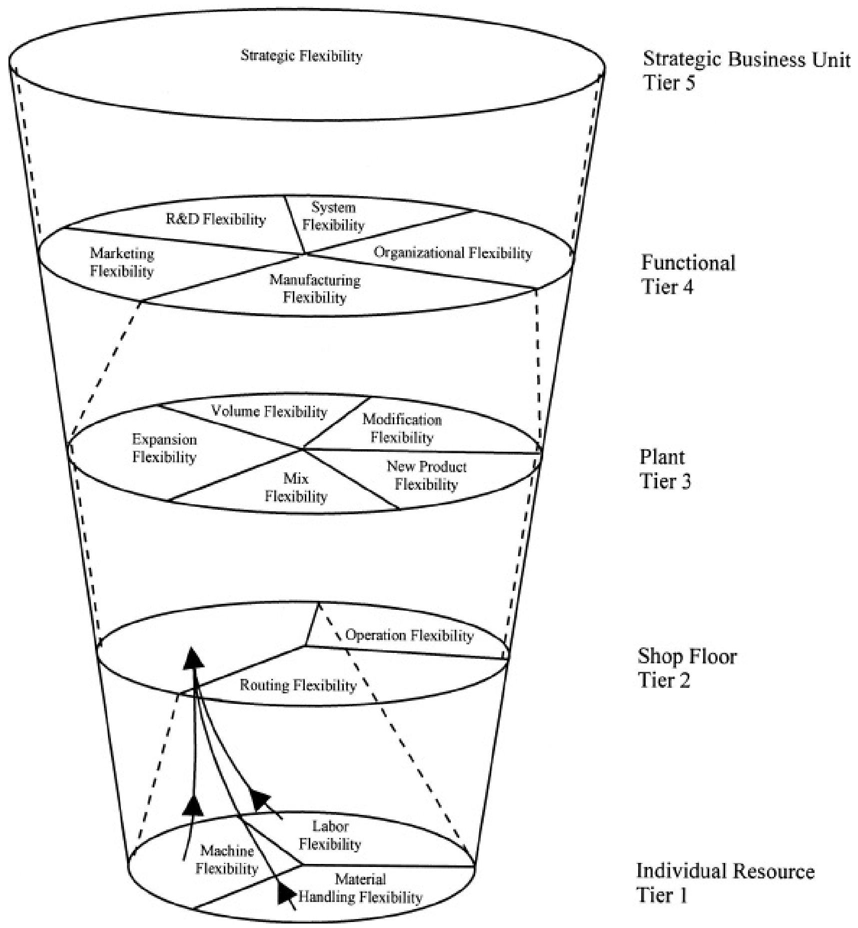

Figure 2.8: Hierarchy of flexibility dimensions (Koste & Malhotra 1999, p. 87).

(2009, p. 10) determine the factory also as the system boundary of the concept. Lanza et al. (2012) extend it to production networks. They argue that the change drivers affect an entire production network as well. Consequently a production network needs to be transformable as well (Lanza et al. 2012, pp. 200–201). However, a broad discussion about how to include a production network into the concept is not available in the transformability research.

Zäh et al. (2004) discuss transformability from a general perspective and explain it as a solution-neutral possibility to react appropriately to unforeseen influences from turbulent market environment. They understand transformability as the potential to react to these turbulences with capabilities outside of prepared flexibilities (Zäh et al. 2004, p. 173).

Wiendahl et al. (2007) develop the transformability concept further and suggest a structure of capabilities to react to changes. They describe that changeability in general can be classified into five classes, including flexibility, transformability and agility. The main focus of the changeability concept remains on the factory level. They define transformability as “the tactical ability of an entire factory structure to switch to another product family. This calls for structural interventions in the production and logistics systems, in the structure and facilities of the buildings, in the organization structure and process, and in the area of personnel” (Wiendahl et al. 2007, p. 786).

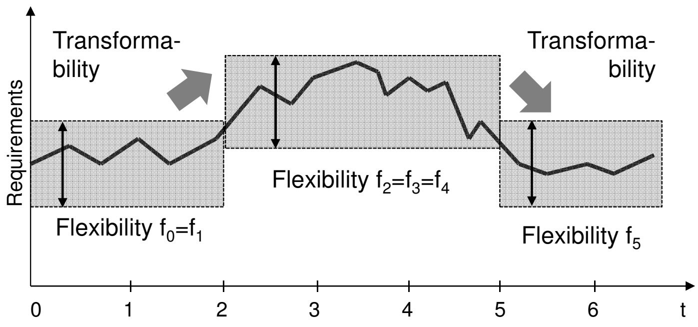

Figure 2.9: Relationship between flexibility in manufacturing and transformability (Nyhuis et al. 2008, p. 25).

Nyhuis et al. (2008), Wiendahl et al. (2009) and Nyhuis et al. (2010) distinguish transformability from flexibility in manufacturing. They define transformability as the capability to react on changes outside of the "pre-defined flexibility corridors". Figure 2.9 illustrates the relation between transformability and flexibility. From their perspective the "implemented" manufacturing flexibility covers the required change to a certain, but limited extent. If the change requires adjustments which exceed the dimension of the "flexibility corridors" the production system has to transform itself (Wiendahl et al. 2009, pp. 121–122). Therefore, a pre-thought solution space is defined within the system can transform itself. Nyhuis et al. (2008, pp. 14–24), Nyhuis et al. (2010, p. 8) and Nyhuis (2010, p. 8) define transformability as the potential of a system to activate organizational, technical and logistical changes outside of available flexibility corridors, in case when needed. This activation is done within time constraints, low investments and under consideration of the interdependencies of the system elements. A transformable production system can be adjusted under various dimensions of change such as changes in the number of produced pieces, technology, quality, time, product and cost structures.

Transformability enables a production system to react on changes which were not foreseen at the time of the planning of the production system. These adjustments require investments in terms of money and time. These investments are activated at the time when the adjustments are realized (Nyhuis et al. 2008, pp. 14–24).
Mersmann et al. (2013) and Klemke (2014) extend the transformability concept with a system view and introduced the systemic transformability. They define it as the potential of a factory to achieve a change in the number of pieces, variants, costs, time and quality, when required. This change is realized through technological, logistical, organizational or personnel adjustments with adapted types, numbers of elements or connections of a system under the consideration of interdependencies of the system elements (Klemke 2014, p. 39). This means that they include the possibility that the changed factory elements can interact with each other.
Nyhuis et al. (2010, p. 8) declare that transformability needs to improve the business situ-

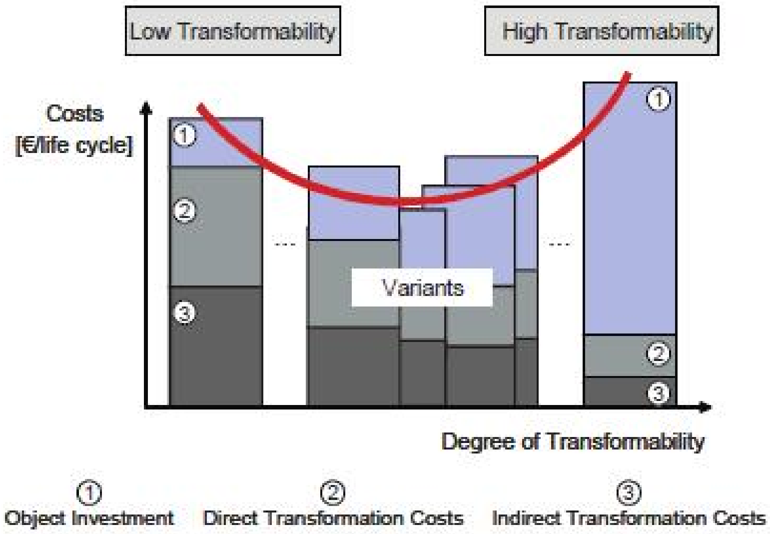

Figure 2.10: Cost development for different degrees of transformability (Wiendahl et al. 2007, p. 793).

ation of a production company. The evaluation of the business impact of transformability is limited to the cost perspective (Wiendahl et al. 2007, p. 793). Nyhuis et al. (2008) as well as Wiendahl et al. (2007) accentuate that every company needs to define its individual level of transformability. The less transformability the better, as maximizing the transformability leads to unnecessarily high costs (Wiendahl et al. 2007, p. 793). Figure 2.10 shows the expected cost development of implementing transformability into the production system of a company. Potential benefits of investments into transformability or achievements of business advantages, such as gaining additional market share by adjusting operations faster, are not considered by the transformability concept.

Hernandez (2003), Wiendahl et al. (2007) and further researchers contribute elements of transformability to use it in practice. The main elements for the application of the concept are:

- Internal and external change drivers,
- Change objects and
- Change enablers.

Change drivers are defined as turbulences which create a need for change on the different levels of a production system. They can be categorized in internal and external change drivers. External change drivers originate from different influencing areas such as turbulences in technology, for example changed product life-cycles, in politics, for instance lower regulation, or in the economy such as changing customer demand (Heinen et al. 2008, p. 21). An example for a major internal change driver is a new company strategy such as entering a new market (Wiendahl et al. 2007, p. 784). Lanza et al. (2012, p. 203) argue that internal change drivers can be divided into defensive (poor product quality, high inventory, etc.) and offensive (proactive company strategy to gain market shares, etc.).

Change objects are defined as the elements of a production system on which the change is realized (Moser 2014, p. 16). Examples are products, processes, facilities or the organization (Wiendahl et al. 2007, p. 784).

The change objects are characterized by different change enablers specified by Hernandez (2003, pp. 54–56). Different definitions of change enablers are discussed in literature such as in Hernandez (2003), (Nyhuis et al. 2008, p. 27), (Wiendahl et al. 2009, p. 125) and (ElMaraghy & Wiendahl 2009, p. 9). Wiendahl et al. (2007) defines them as "certain inherent features or properties which enable the physical and logical objects of a factory to change their capability towards a predefined objective in a predefined time and are not to be confused with the flexibility types or its objectives" (Wiendahl et al. 2007, p. 787). Hernandez (2003, pp. 54–56) names five change enablers:

- Universality,
- Mobility,
- Scalability,
- Modularity and
- Compatibility.

Figure 2.11 explains the change enablers.

2.2.3 Agility

Agility in manufacturing is the third changeability type discussed in this thesis. The concept has been found in literature since the early 1990's. It is also called agile manufacturing, agile production or production agility. Throughout this work agility in manufacturing will be used as a synonym for all of them.

Narasimhan et al. (2006, p. 443) explain that agility in manufacturing "has not received as much conceptual development as lean manufacturing". That is one reason why many different definitions of agility in manufacturing are available with slightly different meanings. In the following different definitions of agility will be discussed.

The "21st Century Manufacturing Enterprise Strategy" by the Iacocca Institute was one of the first publications about agility in manufacturing in 1991. The authors state that the goal of agility in manufacturing is to overcome uncertainty and master change. Technology should be integrated into production and cooperation between companies should

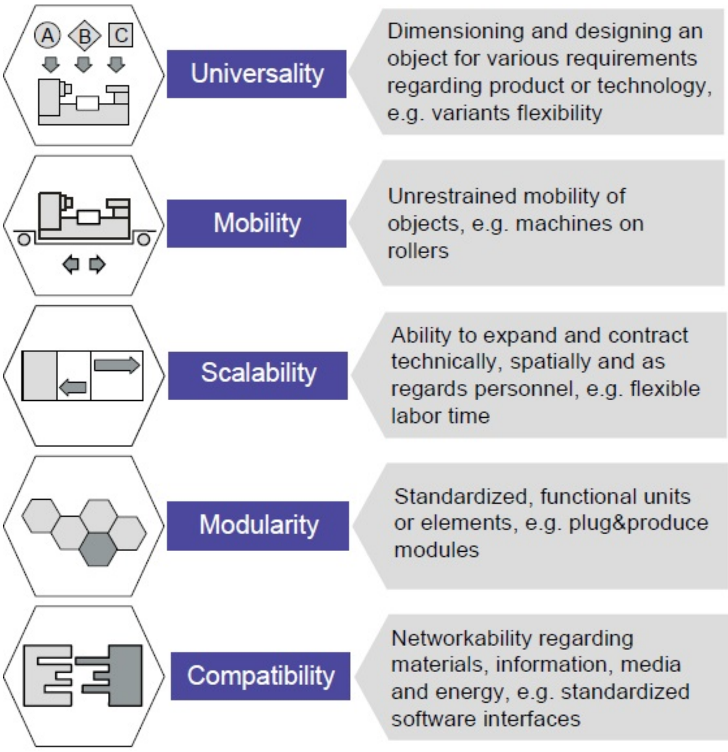

Figure 2.11: Types of change enablers identified by Hernandez (2003, pp. 54–56) and Klemke & Nyhuis (2009, p. 648).

be established. The launch of new products should be done as quickly as possible representing a strong customer focus (Nagel et al. 1991). This means that companies are surrounded by a changing environment which requires them to adapt quickly to changes. The report provides concrete examples and ideas how agility in manufacturing can be achieved.

Kidd (1994) builds on the concept of Nagel et al. (1991) and defines agility in manufacturing as "the integration of organization, highly skilled and knowledgeable people, and advanced technologies, to achieve cooperation and innovation in response to the need to supply the customers with high quality customized products" (Kidd 1994, p. 10). From his point of view reacting quickly to changing customer needs in a volatile marketplace and delivering highly customized products characterize the agility concept (Kidd 1994, pp. 21–23). He summarizes the concept by stating that "being agile means being proficient at change and allows an organization to do anything it wants to do whenever it wants to" (Kidd 1995, p. 2). He provides a collection of abilities a company should possess to react to changes.

Gunasekaran (1998, p. 1223) defines agility in manufacturing "as the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services." Same as for Kidd (1994), for Gunasekaran (1998) also the speed of reaction as well as a customer-focused approach are the core principles of agility in manufacturing. He mentions that a selection of manufacturing concepts such as Just in

Time (JIT) production and Total Quality Management (TQM) are part of the agility concept. Furthermore virtual enterprises are one of the core characteristics of the concept in his perception. Virtual enterprises are defined as the temporarily combination of distributed competencies from individual partners (Gunasekaran & Yusuf 2002, p. 1368).
For Ben Naylor et al. (1999) agility in manufacturing is a combination of the definitions provided by Kidd (1994) and Gunasekaran (1998). They add that the opportunities of the volatile marketplace should be exploited in a profitable way. The inclusion of the profitability into the characterization of the agility concept is an important advancement of the concept.
Yusuf et al. (1999) state that agility in manufacturing "goes beyond speed and it requires massive structural and infrastructural changes" (Yusuf et al. 1999, p. 36). They define it as "the successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast changing market environment" (Yusuf et al. 1999, p. 37). They add that the competitive bases can be achieved by integrating reconfigurable resources and best practices.
Sharifi et al. (2001, p. 858) separate agility in manufacturing into agility and responsiveness. They define agility as "the ability of an organization to effect change in its systems, structure and organization." Responsiveness on the other hand is defined as "the ability of an organization to gather information from its commercial environment and to detect and anticipate changes". In their perspective this means that agility describes the capability of a company to change. Responsiveness specifies an approach how the environment of a company can be analyzed to identify changes and prepare for them.
The definition given by Tsourveloudis & Valavanis (2002) also positions agility in manufacturing as an approach to react profitably to fast changing markets. They define it as "the ability of an enterprise to operate profitably in a rapidly changing and continuously fragmenting global market environment by producing high-quality, high-performance, customer configured goods and services" (Tsourveloudis & Valavanis 2002, p. 330). From their perspective it is difficult to evaluate agility "due to the multidimensionality and vagueness of the concept of agility itself" (Tsourveloudis & Valavanis 2002, p. 329).
The agility definition of Narasimhan et al. (2006) is on a more operational level. They define a production as agile "if it efficiently changes operating states in response to uncertain and changing demands placed upon it" (Narasimhan et al. 2006, p. 443). They underline that agility in manufacturing consists of different flexibilities preparing a company to react on unforeseen events, such as demand shifts. From their point of view a close partnership with suppliers within the supply chain of a company are important requirements to implement agility in manufacturing successfully. Intense cooperation between the company and its suppliers is an important enabler of agility in manufacturing. This means that a company needs to expend its perspective towards its supply chain to

react on changes. Focusing on internal processes to prepare for changes is not sufficient. The supply chain needs to be agile as well to react to the required changes.
The researchers focusing on transformability have a different view on agility in manufacturing. They position it on a strategic level of a company. Wiendahl et al. (2007, p. 786) defines agility as “the strategic ability of an entire company to open up new markets, to develop the requisite products and services, and to build up necessary manufacturing capacity”. In their perspective agility affects on the production network level.
After analyzing the provided definitions three main characteristics describe the agility in manufacturing concept:

- The ability to react fast to a changing environment,
- Realizing this adjustment in a profitable way and
- Having flexibility in its structures and processes to be able to adjust to the changing environment.

These first insights about the different definitions of agility in manufacturing are the basis for the development of an own definition of agility in manufacturing. This definition will be introduced in chapter 4.1.

2.2.4 Conclusion

In the previous section different changeability concepts for production were introduced and discussed. Flexibility describes the intrinsic potential of a system to adapt to changes. Transformability is defined as the change potential of a production system outside of a predefined flexibility corridor. Whereas flexibility does not require investments as the system uses its intrinsic capabilities, transformability needs specific investments in terms of time and financial resources to transform a system. Agility in manufacturing describes the adaption towards changes by leveraging the supply chain of a company and its partners. The impact of the change on the profitability forms the core of the concept. This means that the focus is not limited to the costs for the application of the concepts, such as in the transformability concept. Rather, the revenue potentials are taken into consideration as well.

2.3 Conclusion

Throughout the previous sections, the required terms as well as different concepts how to react to changes in production were introduced and defined. By doing so, the application focus of the methodology was defined. Further requirements for the methodology were identified. In the following requirements and the delimitations for the methodology are summarized. The methodology will be developed to answer the research question. Based on these requirements and the research question from chapter 1.3, the currently available methodologies to evaluate the changeability of production and production networks can be described and assessed. Consequently research needs can be extracted. Meaning, the newness of the developed methodology can be ensured.

2.3.1 Delimitation of research focus

Within the previous sections, basic terms about production, production networks and supply chains were discussed. Additionally concepts on how to react on changes in manufacturing were described. Based on them as well as on the research questions, the research focus for the developed methodology can be defined:

- **Manufacturing of goods:** The purpose of a production is the manufacturing of goods (section 2.1.1). Therefore the delivery of services is not the focus of the methodology.
- **Focus on production networks:** The methodology focuses on production networks with an OEM and its suppliers. The OEM is the focal company of the production network and leads it (section 2.1.2).
- **Evaluation of agility:** The methodology aims to evaluate the agility of a production network (section 2.2.3). The evaluation of other changeability capabilities such as flexibility and transformability is not part of the methodology.
- **Investigation of demand volatility:** Demand volatility is one of the main change drivers which influences a production (Kirchner et al. 2003, p. 255). Therefore the methodology focuses on the evaluation of agility levels as a reaction on demand changes, both short- and long-term.
- **Application during the operations phase of a production:** The methodology focuses on the active operations phase of a production. It is assumed that the production is already up and running. Its currently available agility level needs to be evaluated and, if required, improved.

2.3.2 Evaluation characteristics for newness of research effort

The main purpose of this research effort is to create a methodology which evaluates the agility of a production network by using a stress test approach. Different requirements are necessary to ensure the newness of the methodology developed throughout this research effort. Additionally the requirements are used in chapter 3.2 to assess currently available methodologies to evaluate the changeability of production. The requirements are summarized in the following.

- **Holistic and quantitative evaluation of agility:** The objective of the methodology is to provide a comprehensive evaluation of the production network's agility for the production network management. It is therefore required to evaluate the agility along different agility characteristics. Their evaluation needs to be done quantitatively using specific, operational KPIs. An evaluation for the characteristics needs to be provided. The economic benefits of agility need to be included in the evaluation as well.

- **Production network with focal company:** The evaluation of the production network agility should be done from the perspective of a focal company. Its management is the initiator of the agility evaluation and the recipient of the results.

- **Stress test based approach:** Stress tests are currently mostly used in the financial industry. The methodology developed in the course of this research needs to apply the logic of these financial stress tests in the production environment. The idea to derive scenarios from historical market courses which put stress on a system needs to be adapted to an application for production networks. This enables the methodology to test and evaluate the agility capabilities of the production network in critical situations.

- **Tool for production management:** The purpose of the approach is to evaluate the current agility level of a production network. If required, measures can be identified and evaluated to improve this agility level to the needs of the company. Therefore this methodology is a management tool for the strategic production management of the focal company. The results of the evaluation shall be used to manage the production network strategically and to improve its overall agility.

- **Evaluation of inter-dependencies:** A production network with its different network partners can be seen as a system with many influencing factors and elements (Schuh et al. 2011, pp. 476–477). These factors and elements have many inter-dependencies and mutual influences which require efforts to be predicted. When applying the methodology it therefore needs to be ensured that these inter-dependencies are evaluated. It further needs to be ensured that different operational measures can be evaluated.

- **Identification of improvement areas:** The methodology aims to identify potential areas to improve the agility of the production network. Different agility measures are identified and need to be evaluated according to their impact on the production network's agility.

- **Practicality in different industries:** The methodology needs to ensure a practical way to evaluate different measures about their impact on the overall agility. Therefore a pragmatic approach for data collection as well as data processing of the measures has to be ensured.

3 Related work

Within the following, the related work regarding stress tests and methodologies to evaluate the changeability of a production are presented. Therefore, in section 3.1, the stress test concept is introduced and its current state of application in the financial as well as in other industries is explained. Thereafter, in section 3.2, an overview over the current state of research about methodologies to evaluate changeability is prepared. Approaches and methods are presented that evaluate the flexibility, transformability and agility on a factory, production network and supply chain level. The chapter closes with the identification of the research gap in section 3.3. For that reason the presented stress test concept as well as the changeability evaluation approaches are assessed according to the evaluation characteristics introduced in section 2.3.2.

3.1 Stress tests

Stress test is a concept which is currently and mainly used in the finance industry. With the help of stress tests companies are able to analyze in detail the potential implications of unexpected events such as catastrophes and crises on their operations. Actions to prepare proactively for them can be derived. As the stress test concept is mostly known in the finance industry, an overview of its usage in banks and insurance companies will be given in the following section 3.1.1. Section 3.1.2 provides an overview of first applications of the stress test concept outside of the finance industry.

3.1.1 In finance industry

Within the following, the financial stress tests are introduced. Therefore an overview is given, followed by the explanation of the objectives. Thereafter the process and methods are described and results of a financial stress test are illustrated.

Overview

The term 'stress test' is defined as "a test designed to assess how well a system functions when subjected to greater than normal amounts of stress or pressure" (Oxford University Press 2015). Since the early 1990's the concept also appears in the financial institution sector. Banking supervisors and regulators in Europe and the US require a regular execution of stress tests from their financial institutions as an approach to assess and monitor market-risks (Blaschke et al. 2001, pp. 6–7).
The usage in banks increased after the Financial Crisis between 2008 and 2009. This is due to the observation that banks which paid a lot attention to stress tests before the crisis and used them as a risk management tool supervised by the banks' senior management, navigated comparatively well through the Financial Crisis (BCBS 2009, p. 2).
Financial stress test describes a range of techniques to "assess the vulnerability of a portfolio to major changes in the macroeconomic environment or to exceptional, but plausible events" (Blaschke et al. 2001, p. 4). Following Blaschke et al. (2001, p. 4) the stress tests aim to make risks transparent by evaluating potential losses on a portfolio in abnormal markets. It is defined as a key risk management tool within financial institutions such as banks and insurances. It allows them to take a "forward-looking view in their risk management, strategic planning and capital planning" (CEBS 2010, p. 2). Furthermore, it allows to create a risk profile of an institution and to test its resilience against internal and external shocks. Results of the stress test are useful on all levels of management in a financial institution. The trading level can gain insights about the potential vulnerability of a particular financial position or product. For the executive level "stress tests provide a way of comparing the risk profile of the institution with the risk appetite of the owners, helping to guide decisions on the optimal allocation of capital within the institution" (CEBS 2010, p. 2).
In the insurance industry stress tests are used as well. Even though its dissemination and distribution is not as widely used as in the banking industry. This results in a lower level of regulation and design details of the approaches. In this industry stress tests are used especially for two purposes: first with the goal to identify insurance companies with a critical equity capitalization. For this kind of stress tests, authorities provide pre-defined scenarios. The second purpose is to use stress tests for internal risk management. In this application case the companies can define their own scenarios (Bennemann & Schalk 2010, p. 24).

Objectives of financial stress tests

Due to the observed benefits of conducting stress tests during financial crises, the banking authorities, such as the Committee of European Banking Supervisors (CEBS) in Europe, issued laws making the tests mandatory for banks. The released regulations have the goal

to improve the risk management and assessment of banks to be better prepared for future financial crises.
Fremdt & Völz (2010, p. 5) identify three purposes for financial stress tests:

1. Risk transparency: They help to provide a transparent overview of potential risks which can affect an institution and would influence its solvency.

2. Management tool: They are used as a steering and management tool of risks which cannot be realized in model based measures.

3. Assessment tool for authorities: They are used as a checking tool by national or international authorities which provide specific parameters to run the sensitivity or scenarios analysis with the goal to check the situations of their financial institutions.

Process and methods

The efforts for the realization of stress tests differ. They can range from "from simple sensitivity analysis on single portfolios to complex macroeconomic scenario stress testing on a firm-wide basis" (CEBS 2010, p. 2). For Ludwig et al. (2010, p. 65) stress tests consist of sensitivity and scenario analyzes which are combined with a structured process to define the scenarios which have to be analyzed. The realization of stress tests follows a structured process. Figure 3.1 shows a decision sequence for the realization of stress tests in the banking industry.

The first step in the sequence selects the risk model type. A decision needs to be made if the stress test focuses on individual risks, such as credit risks or interest rate risks, or encompasses multiple risks. The next element is the selection of stress test type. There are three types of stress tests available driven by the number of factors that will be included. The first one involves the impact estimation of one single risk factor. For that purpose a sensitivity analysis should be applied (Blaschke et al. 2001, p. 4). EBA (2014, p. 22) suggests a specific methodology for a credit risk stress test.
Saltelli et al. (2004, p. 45) define sensitivity analysis as "the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input". The definition of Saltelli et al. (2004) is often used as a local measure, meaning that the effect of a given input on a given output is investigated (Saltelli et al. 2004, p. 42). In environments, such as in the analysis of risks in regulatory compliance analysis or decision support, sensitivity analysis is applied on a more global measure. This means that the aim of the analysis is to set priorities "to determine what factor most needs better determination, and to identify the weak links of the assessment chain (those that propagate most variances in the output)" (Saltelli et al. 2004, pp. 42–44). A model, as mentioned in the definition, can be data- or law-driven, which means

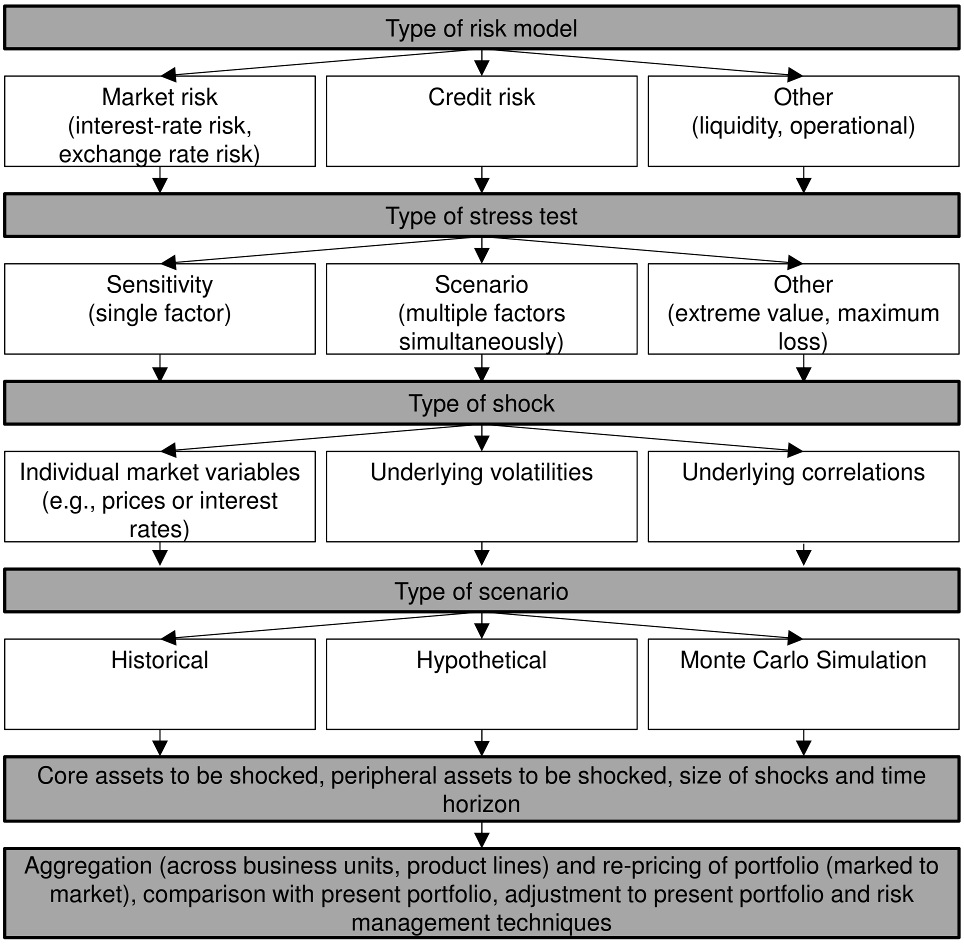

Figure 3.1: Decision sequence for a stress test in the banking industry (Blaschke et al. 2001, p. 5).

that “a data-driven model tries to treat the solute as a signal and to derive its properties statistically”, whereas a law-driven model tries “to put together accepted laws which have been attributed to the system, in order to predict its behavior”. Further a model can be used for diagnostic or prognostic purposes” (Saltelli et al. 2008, p. 5).
In the case that multiple factors should be assessed simultaneously, a scenario analysis has to be used. This means that scenarios can be designed to “encompass both movements in individual market variables (such as prices) and changes in the underlying relationships between different asset markets (such as correlations and volatilities)”. This defines the type of shock used in the stress test (Blaschke et al. 2001, p. 4).
The third type of stress tests described as “Other” in figure 3.1 are known as reverse or inverse stress tests. They as well allow to evaluate the risk which lays in different portfolios. This is realized by identifying those scenarios with an underlying dynamic of risk drivers which cause the business models of an institution to fail (CEBS 2010, pp. 12–20). It means those market constellations are identified on which the portfolio will collapse (Ludwig et al. 2010, p. 65). Ludwig et al. (2010, pp. 76–82) mentions three approaches how reverse stress tests are run:

- Factor-push,
- Maximum-loss and
- Factor-group method.

In the factor-push-method one risk factor is changed, while all other risk factors are kept constant, until the current portfolio reaches its lowest value. In the maximum-loss-method the maximum loss of a portfolio is evaluated by varying all of the risk factors at the same time. The factor-group method is the third methodology and functions by combining all strongly correlated risk factors to groups and than applying them on historical stress tests. It can also be applied to the maximum-loss method to limit the required computation power by reducing the number of changeable risk factors as done in the maximum-loss-method.
With the type of shock selected, the scenario type has to be selected. Ludwig et al. (2010, p. 65) lists three scenario types for banking stress tests:

- Historical scenarios,
- Hypothetical scenarios and
- Monte-Carlo-Simulations.

Historical stress tests use data and scenarios from relevant time frames of the past and apply them to the current setup of a bank. In the banking stress test especially historical crisis situations are considered. Examples of events are the Asia crisis 1997/98 or the

crisis in Russia 1998 (Ludwig et al. 2010, pp. 67–76). An advantage of this approach is the intuitive application which leads to a high acceptance of the approach and the outcome by the involved managers. A disadvantage is the backward look and that the gained insights may lose relevance as the markets and institutional structures change (Blaschke et al. 2001, p. 6). The usage of historical events are a core characteristic of banking stress tests. By applying these historical scenarios it is assessed how a current portfolio structure with all of its elements would react to events that have already happened in the past.
Hypothetical scenarios are built of not observed, but nevertheless potentially realistic situations, often derived from expert input or "as-if" thoughts (Fremdt & Völz 2010, p. 5). They offer more flexibility for their formulation. They allow a view into the future and include recent developments and current vulnerabilities. This means that an anticipative part can be included making the hypothetical stress test a forward looking methodology. When applying the scenarios different inter-dependencies and feedback loops among the factors arise and the system-wide dynamics are taken into account. When defining the scenarios it should be made sure to include exceptional, but nevertheless plausible events. This rises the acceptance of the scenarios and their results by the involved employees (CEBS 2010, pp. 12–20). The disadvantage of this approach lies in the potentially reduced acceptance compared to historical scenarios of the approach and the results. It requires effort and reasoning to convince all the involved people about the results, especially when exceptional events and periods are included in the scenario (Blaschke et al. 2001, p. 6).
Hypothetical scenarios can be divided into standardized and macroeconomic scenarios. Standardized scenarios are set by official authorities such as for international banking. The second scenario type uses macro economic crisis scenarios and transfer their impact on banking relevant risk factors. They are created from unreal information which usually result in a lack of acceptance by the management involved (Ludwig et al. 2010, pp. 67–76). Hambach & Albrecht (2014) provide an overview of different scenario techniques.
Monte-Carlo-Simulations are further defined as "a scheme employing random numbers [...] used for solving certain stochastic or deterministic problems" where time plays no substantive role (Law & Kelton 2000, p. 90). For financial stress tests this means "to simulate the impact of a wide variety of different combinations of variables, and to include the effect on portfolios with non-linear characteristics, such as complex foreign exchange option portfolios " (Blaschke et al. 2001, p. 6). They conclude that the approach is computationally intensive and a high level of risk management expertise is necessary.

Results

The results of banking stress tests are used by banking supervisors to assess the stability of individual banks. CEBS (2010, p. 26) explain that supervisors review the output of the stress tests "in order to assess the resilience of individual institutions to adverse economic conditions and whether they are able to maintain sufficient capital and liquidity.

In doing this, supervisors should take into account details of movements in capital and capital needs, and liquidity and liquidity needs, under stressed conditions". In practice the results include information about the capital endowment of the banks and how it develops for every scenario. Exemplary results of the EU-wide stress test conducted by the European Banking Authority (EBA) in 2014 can be found at EBA (2015).

3.1.2 In other industries

Outside of the financial institutions the stress test concept is used to a limited extent. An online literature review conducted by the author[3] about stress tests in operations or businesses resulted in a limited number of results. Only three published approaches fitting the topic of the work could be identified. They will be introduced within the following.

Stress test methodology for supply chains by Jain & Leong (2005)

Jain & Leong (2005) propose an approach to stress test the supply chain of SME supplying parts to an OEM. Their approach simulates different demand scenarios and evaluates strategies to meet the defined volumes with a supply chain under high demand stress.
To realize the simulation three scenarios of demand volume levels of the OEM were used:

- Normal operation,
- Surge operation with twice the volume level of the normal operation and
- A scenario with four times the volume level of normal operations (Jain & Leong 2005, p. 1652).

The simulation included the assumption that there is a 13-week time period to ramp up the capacities of the supply chain to the scenario with four time demand volume. The simulation is realized using software ARENA. The performance of the simulated supply chain was evaluated using performance measures such as supply chain inventory or customer order backlog (Jain & Leong 2005, pp. 1653–1654).

Purchasing stress test by Wildemann (2015*a*)

Wildemann (2015*a*) suggests a stress test for the purchasing activities of a company. The approach is used to identify, analyze and handle risks in purchasing. He positions the

[3] Realized between July and August 2015, using Google Scholar (http://scholar.google.com/, ScienceDirect (http://www.sciencedirect.com/) and Scopus (http://www.scopus.com/)

approach as a risk management system. The increasing risk in purchasing is characterized as a result of different trends in sourcing such as globalization of sourcing markets or increased cooperation between OEMs and suppliers. Further, changes in the general conditions, for example macro-economic fluctuations or legal changes regarding product liabilities lead to the increase of risks (Wildemann 2015*a*, pp. 3–39).
Wildemann (2015*a*, pp. 73–77) publishes a stress test process illustrated in figure 3.2. This process is designed to be applied by industry companies. The process consists of five steps. The first step analyzes the current situation of the company to identify potential risk factors. This is done in order to prioritize the fields of study. Instruments that are applied during this phase are, for example, audits, interviews or Strengths, Weaknesses, Opportunities and Threats (SWOT)-workshops[4]. Based on these insights, stress scenarios can be defined in step two. The goal of the second step is the definition of extreme, but still plausible pictures of the future to investigate the robustness of sourcing. Tools such as scenario techniques, extrapolation or simulations are used. In the third step the strategies, structures and processes of sourcing are assessed according to its preparedness for the future. During this step tools such as Monte-Carlo-simulation, scoring models or interdependency analysis are applied. After having created potential future developments and having assessed how well the purchasing is prepared for it, the definition of measures and its planning is done in the fourth step. To ensure the selection of the right measures, instruments such as prioritization, employee training and a solid implementation controlling of the measures need to be used. The same measures can also be applied in the fifth step which is the derivation and implementation of immediate measures. The practical application of the purchasing stress test is proved by various case studies (Wildemann 2015*a*, pp. 346–375).

The methodology of Wildemann (2015*a*) contains many ideas and approaches of the finance stress test that have been transferred to the industry and purchasing. Examples include the scenario technique and the definition of stressing scenarios for simulations. The realization of the methodology happens on a high level of a company without assessing the operational impact of the risks. Furthermore, the approach uses potential future scenarios which often lack acceptance of the involved management (Ludwig et al. 2010, pp. 67–76). An assessment of how a company and its purchasing department would react to scenarios derived from historical events which were stressful for the company or industry is not done. Additionally a simulation on the operational level how a company can react on the stress scenarios is not part of the process.

[4]SWOT-workshops are structured discussion about the Strengths, Weaknesses, Opportunities and Threats of a business Wildemann (2015*a*)

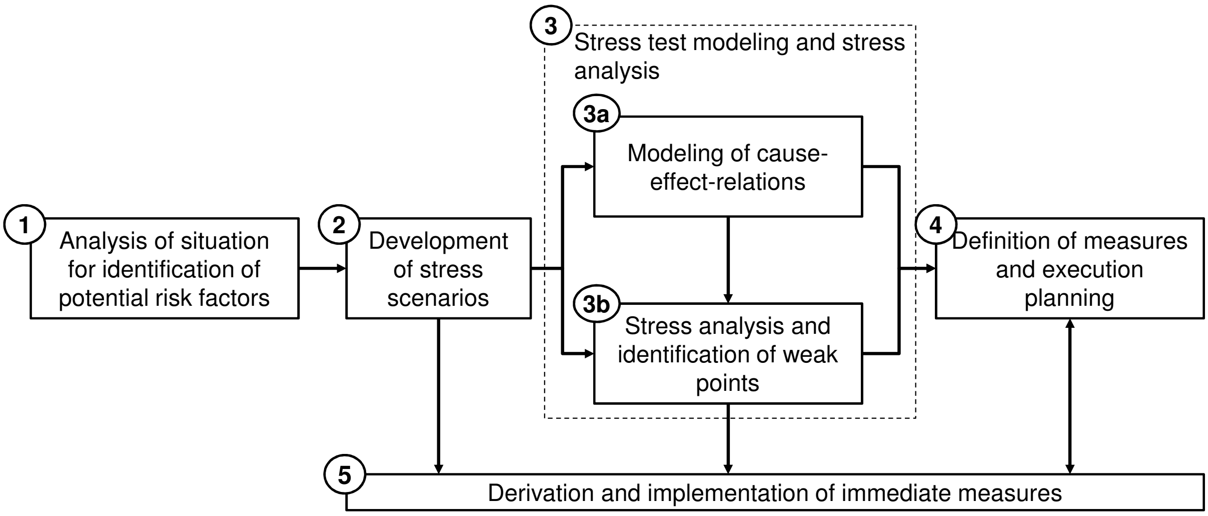

Figure 3.2: Approach for purchasing stress tests, translated from Wildemann (2015*a*, p. 73).

Stress test for business models by Wildemann (2015*b*)

Wildemann (2015*b*, pp. 10–117) publishes a further approach about stress tests of business models. He outlines that a company as a whole needs to be assessed about its robustness to external changes that might occur in the future. It is required that every element of the value chain needs to be evaluated. The elements of the assessment are purchasing, production, sales, logistics, research and development, management and organization as well as financing.
The business model stress starts with the identification of the individual risks of every value chain element. In the next step these risks are aggregated to a holistic evaluation. While creating insights about the risks and their impact on the company, concrete levers need to be identified to prepare for future developments. They help to prepare for future challenges as well as opportunities for the company. The following levers are named as starting points and guidelines for potential future principles: a purposeful cost management, customer orientation, flexibility, organization design, network and supply chain management as well as the usage of uncovered resources.
The concept for a business model concept proposed by Wildemann (2015*b*, pp. 10–117) is a broad and holistic approach. It underlines the requirement to prepare on all steps of a value chain for potential future developments. The approach remains on a high and strategic organizational level of a company. Concrete tools to assess the robustness of processes and production are not included in the concept. Some concrete levers and characteristics are mentioned which help to prepare for unknown future developments. However a method how to quantitatively evaluate the current state of preparedness for future developments is not provided.

The stress test concept is moreover discussed in other application areas. An example is the evaluation of the financial preparedness of the German energy utilities for the exit of the nuclear power (Lange & Houston-Waesch 10.10.2015). The company 'Warth & Klein Grant Thornton AG' realized a stress test and published their findings in a report Warth & Klein Grant Thornton AG (2015). Nevertheless a detailed and academic review of the used approach is not available. Therefore the approach is not assessed in this thesis.

3.1.3 Conclusion

Within the previous section the stress test concept currently and mainly used in the financial industry has been introduced. Structured along the decision steps of Blaschke et al. (2001) the different types, goals and processes to realized financial stress tests were explained. Stress tests in the finance industry use a quantitative approach to evaluate the risks, such as credit or market risks, which a portfolio of financial products could affect. The impact of, for instance, shocks in private consumptions or increase in credit default swaps on the portfolio is calculated. This requires a broad and detailed model of all the portfolio elements and factors. The differences between sensitivity, scenario and reverse stress tests have been discussed. Further the concept of historical and hypothetical scenarios was introduced.
Besides the financial industry, stress tests have been rarely used. Based on a literature review only three further stress test concepts could be identified. Jain & Leong (2005) introduces a simulation based methodology that enables the evaluation of a supply chain according to strong demand changes. In Wildemann (2015*b*) and Wildemann (2015*a*), Wildemann suggests two approaches to assess business models and the purchasing processes of companies according to their resilience against changes by using a stress test based approach.
The concept was furthermore used to assess the financial preparedness of Germany's planned exit from nuclear power in Warth & Klein Grant Thornton AG (2015), but a broader theoretical introduction about how the stress test was realized is not available. Therefore the concept was mentioned, but not included into the methodology discussion.

3.2 Concepts to evaluate flexibility, transformability and agility

As outlined in chapter 2.2, different changeability concepts are available to react to changes in production. Even-though the concepts differ, available approaches for all three will be introduced to evaluate the current changeability level of a production. The evaluation is required to derive measures how to improve it. To achieve that objective

evaluation methodologies are available in research. In the following they will be introduced and discussed.
The presented evaluation methodologies to evaluate flexibility, transformability and agility are structured along their operational level of application: the first chapter discusses methodologies for factories and the second one introduces them for production networks and supply chains.

3.2.1 In factories

Throughout the following, concepts are introduced which evaluate and plan the level of changeability on a factory level.

Methodology for transformability evaluation using material flow simulation by Albrecht (2014)

Albrecht (2014) suggests a methodology to evaluate the transformability of production for medical devices. This industry is characterized by a rigid regulation and a job-shop production with a high product variability. His methodology uses a Discrete Event Simulation (DES) to evaluate the material flow of the production. The objective of the methodology is to identify and evaluate these process steps which hinder the production to fulfill defined scenarios.
His methodology consists of four steps:

1. Analysis of the investigation area,
2. Build up of the simulation model,
3. Evaluation of the production using the simulation model and
4. Visualization of the results.

During the analysis of the investigation area a value stream analysis is done. Different indicators to estimate the required transformability as well as its risk of change from a regulatory perspective are collected. Scenarios about future developments of different change drivers are created.
In the second step the simulation model of the production is created. It is verified and validated with the help of different production experts of the company.
The third step consists of experimenting with the simulation model. The goal is to assess the influence of the scenarios on the production system. During the experimentation those production steps are identified which hinder the production system to fulfill the scenarios. Also the potential impact of transformability on the production system is simulated. The

production steps are analyzed by simulating and interpreting specific operational KPIs. The results of the evaluation are summarized and illustrated using an extended value stream map (Albrecht 2014, pp. 87–130).
The evaluated production steps include an outsourced step, nevertheless the focus of the methodology lays on the production in a factory. The used scenarios describe potential future developments, but are not meant to explicitly stress the production system. Different operational KPIs are suggested to quantify the transformability, although a consistent KPI system is not provided.

Methodology to evaluate and plan capacity flexibility by Gottschalk (2005)

The methodology of Gottschalk (2005) focuses on demand volatility. He suggests an approach to assess and plan the required production volume flexibility of a production system. His planning tool uses flexibility profiles consisting of time-capacity-diagrams to determine and illustrate the most rapid and maximum possible changeability of a production system. The flexibility profiles explains the currently available changeability level of a production system. Figure 3.3 illustrates an example. It enables the evaluation of different flexibility measures and their inter-dependencies on the time-capacity scale. The measures are evaluated according to their capacity contribution, their implementation time and required costs. The suggested approach can be applied for individual production systems as well as for connected ones (Gottschalk 2005, pp. 60–93).
Furthermore, an approach is suggested to plan and evaluate the implementation of capacity adjustment strategies. Gottschalk (2005) includes in the approach an assessment of the required capacity and a structured planning of the measures to fulfill the capacity (Gottschalk 2005, pp. 60–93).

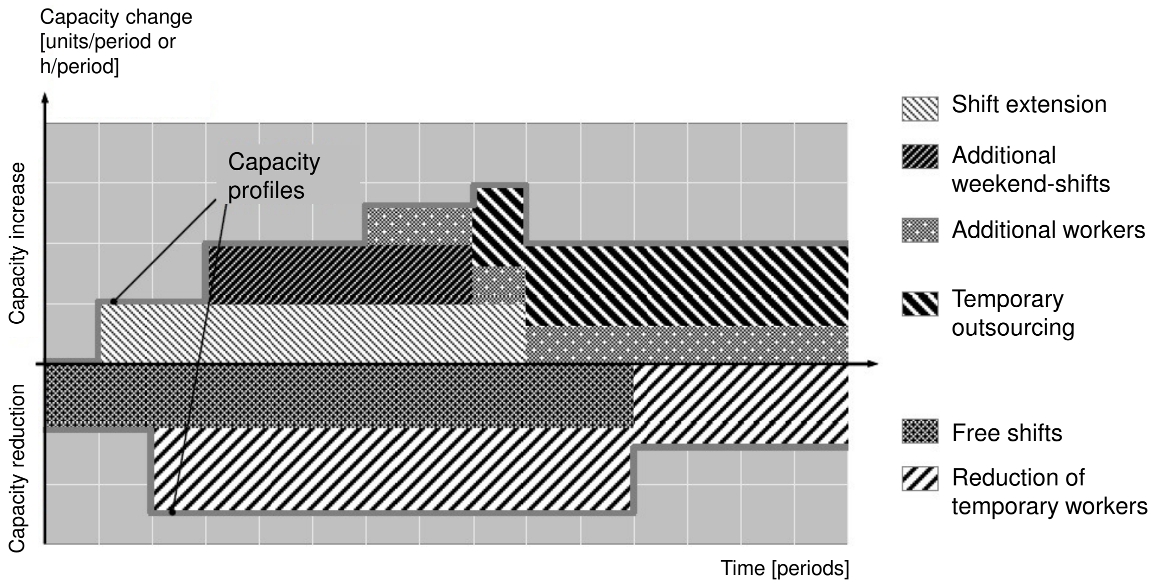

Figure 3.3: Example of a flexibility profile of a working system (Gottschalk 2005, p. 78).

Methodology to evaluate transformability by Heger (2007)

Heger (2007) proposes a methodology to plan and quantify the transformability of factory objects, called "Integrative Evaluation of Transformability". Factory objects can be categorized into technology, organization, space, labor and leadership, whereas the methodology limits its focus on the first three categories (Heger 2007, p. 71). His approach focuses on the planning phase of a factory and enables the monetary and non-monetary evaluation of the factory's transformability. The approach consists of three steps:

1. Analysis of change potential value ("Wandlungspotentialwert-Analyse"),
2. Profitability analysis of the change ("Wandlungswirtschaftlichkeits-Analyse") and
3. Value benefit analysis of the change ("Wandlungsnutzwert-Analyse")

In the first step the change potential is determined for every factory object. To evaluate it, detailed characteristics and quantification types per factory object are provided. The result of this step is current, target and plan values for each factory object regarding every characteristic of its change potential.
In the second step, the net present value method is used to evaluate the identified factory object alternatives. The calculation model calculates the profitability of the transformability specific alternatives. It includes uncertainty and the financial payment flows of each alternative into the model.
In the third step a value benefit analysis is used to evaluate the non-monetary benefit potentials of the created alternatives of the factory objects.
The results are options of factory objects which are appraised according to their transformability potential. Based on these evaluated options a decision can be taken.
The method requires effort to evaluate the transformability of a factory. The approach is a tool for factory planners which want to evaluate and plan the required transformability of a new factory in a detailed way.

Methodology to evaluate transformability by Klemke (2014)

Klemke (2014) introduces a methodology to plan the systemic transformability of a factory. The objective is to evaluate it along the dimensions variants, number of pieces, costs, time and quality under consideration of all factory elements and its inter-dependencies. The methodology consists of two parts:

- A change monitoring and
- The transformability evaluation.

The change monitoring part identifies change drivers of a company and analyzes their impact on the company. The impact is evaluated by analyzing how the change dimensions affect a factory. Examples for the change dimensions are number of variants or cost per pieces. As a result those parts of a factory are identified which need adjustments to fulfill the required change.
The transformability evaluation starts based on the findings of the change monitoring: If the monitoring identifies areas where a change is required in the future, the transformability evaluation is realized. The goal is to analyze the transformability and derive potentials for its increase. Part of the methodology are different catalogs with change drivers and elements of factory objects that can be changed.

Methodology to evaluate the business benefits of transformability by Möller (2008)

The methodology of Möller (2008) suggests a financial evaluation of the factory transformability. The goal is to financially assess different technical measures to increase the transformability (Möller 2008, p. 87). For this purpose he uses the real options approach derived from financial theory and applies them for the evaluation of transformability.
He assumes that the technical measures to increase the transformability of a factory are a bundle of real options. By combining factory planning, life-cycle evaluation and real options he ensures that all the additional information gained during the execution of a transformability project are included in the decision making process. He uses a model of the production which includes different uncertainties of a transformability project and defines a hierarchical, life-cycle oriented cost model.
The benefits of the approach of Möller (2008) are the thinking in options as well as an evaluation of the risk structure of different transformability measures. The practical application of the methodology is questionable. The user of the approach needs knowledge about complex financial theories to understand and accept the approach.

Approach to measure agility by Tsourveloudis et al. (1999) and Tsourveloudis & Valavanis (2002)

Tsourveloudis & Valavanis (2002) publish an approach to measure agility in enterprises as well as in manufacturing systems. They propose a framework to measure the enterprise agility. They use a fuzzy logic to determine quantitative agility parameters and summarize it in the calculation of an agility index. For that Tsourveloudis & Valavanis (2002, p. 332) the overall agility is decomposed into the following divisions:

- Production infrastructure,
- Market infrastructure,

- People infrastructure and
- Information infrastructure.

For each of the divisions Tsourveloudis & Valavanis (2002) define specific parameters which describe the divisions. For production infrastructure, for example, the parameters changeover efforts, variety of loads or range of adjustments or adjustability are used. These parameters are then evaluated by experts based on their knowledge regarding the manufacturing system in scope. Based on the fuzzy logic these divisions are then merged to calculate the agility index of a manufacturing system.
The approach of Tsourveloudis & Valavanis (2002) contributes to the quantitative evaluation of the agility of an enterprise and a manufacturing system. The approach is knowledge-based and therefore it is not suitable to be used in daily business to manage the agility of production.

Methodology to design scalable production steps by Wagner (2012)

Wagner (2012) presents a methodology to determine the required level of flexibility and scalability and to plan the production system accordingly. The methodology differentiates between flexibility and scalability. Scalability describes the capacity adjustment of a production system outside the defined flexibility corridor (Wagner 2012, p. 20). The focus of the application area lays on a factory. He introduces a control loop with four stages:

1. Analysis and evaluation,
2. Usage of flexibility,
3. Usage of scalability and
4. Design of scalability.

During the analysis and evaluation step the historical course of the produced pieces is analyzed and estimates for the required capacities using forecasting methods are derived. The maximum possible capacity, as well as the financially minimum capacity are determined. The financial minimum capacity is calculated based on contribution margins and production costs. These defined capacities are input to create the flexibility corridors.
In the second step the available flexibility measures are activated. If required, during the third step, potential short, mid and long-term measures are activated to adjust the capacity to the requirements. As mid and long-term measures usually require investments, the management of a company is involved in the decision process.
If the available scalability is not sufficient, stage four aims to design additional scalability

measures. To ensure a quick and cost optimal realization implementation plans are created during the fourth step (Wagner 2012, p. 46).
The methodology is characterized by a practical and pragmatic approach. It enables the evaluation of one measure at a time which means that inter-dependencies between different measures are not assessed.

Methodology to evaluate and optimize flexibility by Wemhöner (2006)

The goal of the methodology developed by Wemhöner (2006) is to evaluate and optimize the flexibility of automotive body assemblies. Besides the analysis of their flexibility, the expected benefit of the assembly options are calculated in the planning phase. The methodology focuses on product mix flexibility and volume flexibility.
To evaluate the flexibility, Wemhöner (2006, pp. 126–131) uses different KPIs. They include:

- Product allocations,
- Grade of re-usability of production equipment,
- Technical and organizational capacities as well as
- The production flow.

The methodology of Wemhöner (2006) consists of three modules:

1. The first module creates scenarios to reflect potential market and demand developments. To include the dynamic and uncertainty of the developments, different probabilities of occurrences of the scenarios are defined.
2. The second module creates a model of the car body production system. It therefore considers the identified core flexibility parameters product allocation and dimensioning of capacity. Part of this module is also the inclusion of a cost assessment of the planning alternatives.
3. The third module focuses on simulation and evaluation. It connects the different modeled production systems and market developments. The economic evaluations of the alternatives are calculated. The simulation results are evaluated and illustrated. “Flexibility windows” are introduced to illustrate the costs and benefits of the flexibility for every planning alternative.

The advantage of the methodology is to show the economic benefits of flexibility already during the planning phase of production. Even-though only roughly estimated data is available. The explicit goal of the illustration step is to prepare the results the way that flexibility decisions can be taken on an executive-level (Wemhöner 2006, p. 195).

Transformability index by Witte (2004)

Witte (2004) provide an index to quantify transformability. It consists of the costs and time for the required change. The underlying idea of the index is that the required future change of a factory can be foreseen by defining specific scenarios. These scenarios are converted to concrete measures to adjust the production and logistic system as well as the factory structures and buildings. The results are change paths of the factory for every scenario. Figure 3.4 illustrates the concept including the change points and change paths. The change paths describe a potential future development of the factory. A set of measures representing a section of that change path are included as change points. For every change point the transformability index can be calculated. Its calculation is outlined in formula 3.1.

$$WF_{1000} = \frac{1000}{\sum_{n=1}^{m} (KW_n \times weighted\ ZW_n)} \tag{3.1}$$

WF means "transformability index". KW stands for the change costs which are required at each change point n. ZW is the required change time at every change point n.
The authors explain that the challenge is to calculate cost and time for change with the right ratio to each other. To overcome this challenge, they suggest weighing the time for change in an appropriate manner in the formula (weighted ZW). They articulate that it remains necessary to create specific weighting profiles for every situation (Witte 2004, p. 45).

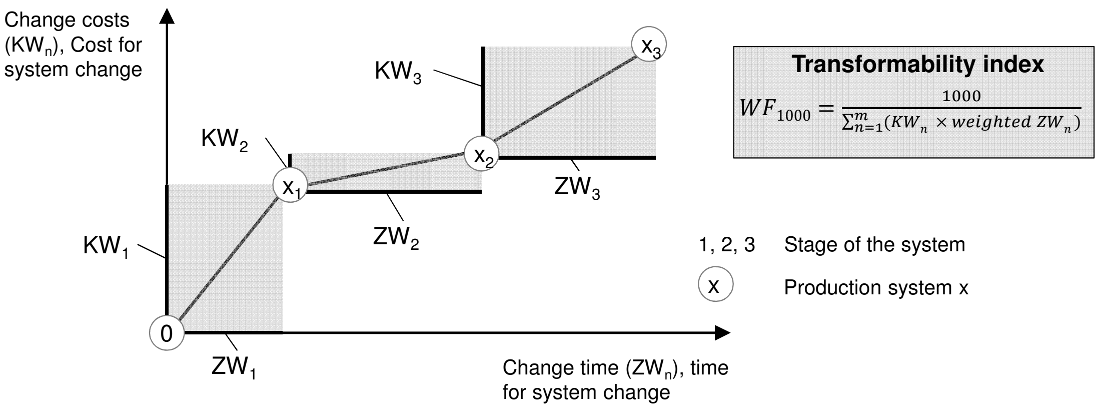

Figure 3.4: Illustration of the transformability index, translated from (Witte 2004, p. 45).

The transformability index suggested by Witte (2004) delivers a quantitatively evaluation of the transformability of a factory. The approach is a tool to evaluate the transformability of different factory options in the planning phase of a factory. An operational evaluation or measurement of transformability is not possible with the approach.

3.2.2 In production networks and supply chains

In the following concepts are discussed which evaluate and plan changeability on the production network and supply chain level.

Agilean index by Azevedo et al. (2012)

Azevedo et al. (2012) propose an index to assess the leanness and agility of an automotive supply chain. The aim of the index is to create transparency about the leanness and agility of every supply chain partner as well as of the entire supply chain (Azevedo et al. 2012, p. 92). Furthermore the results can be used as a benchmarking framework to compare the leanness and agility performance of supply chains of different companies.
For the assessment they introduce the Agilean-index. This index consists of two indicators, one for agility and one for leanness. Both are created by an hierarchical relationship of sub-indicators of different agile and lean supply chain practices. The Agilean index is calculated by the implementation level of weighted leanness and agility practice for every partner of the supply chain (Azevedo et al. 2012, pp. 86–87).
Based on a literature review a list of agile and lean supply chain practices were collected. Example practices are:

- Agile practices
  - To use IT to coordinate/integrate activities in design and development or
  - Ability to change delivery times of suppliers' orders.
- Lean practices
  - Pull flow or
  - Just in time (focal company to first-tier customer).

To assess the usage of the mentioned supply chains practices supply chain management experts of the involved companies are interviewed about the implementation grade of the practices. The experts have to select whether the practice was "implemented" or "not implemented" (Azevedo et al. 2012, pp. 87–89).
The index offers a structured way to evaluate the supply chain agility using one number. This characteristic is helpful for the usage in benchmarking efforts. The approach appears to be unpractical for the management of the supply chain agility. Furthermore it cannot be used to assess the supply chain agility from an operational point of view.

Agility Index for Supply Chains by Lin et al. (2006)

Lin et al. (2006) propose an approach to calculate a fuzzy agility index for supply chains. It evaluates the agility capabilities of a company's supply chain using a three step approach. In the first step an evaluation of the agility drivers and the own agility capabilities is done. It is realized using workshops and interviews with responsible managers. The results are expressed in linguistic terms and represent the required agility level of the supply chain. Then, the agility capabilities of the supply chain are transformed into quantitative ratings and the agility index is derived. In the third step the proposed agility index is calculated and major barriers to improve the supply chain's agility are quantitatively identified. This helps a company's management to derive measures to improve the supply chain agility (Lin et al. 2006, pp. 288–291).
Following Lin et al. (2006, p. 287), the assessed core agility capabilities are

- Responsiveness,
- Competency,
- Flexibility and
- Quickness of a supply chain.

Furthermore, a list with high level attributes to measure supply chain agility such as collaborative relationships and process integration as well as corresponding sub-attributes is provided (Lin et al. 2006, p. 293).
Their approach evaluates the agile supply chain capabilities in a very structured way. Nevertheless the fuzzy logic approach using linguistic terms to measure and evaluate the agility of supply chain lacks reliability and practicality. The objective of using high level attributes and the fuzzy logic to measure supply chain agility is to provide an approach which is as generic as possible. Therefore it can be applied in various industries and companies. A list with concrete numbers of characteristics and performance indicators to evaluate the supply chain in a quantitative way is not provided. For that reason the approach cannot be used to manage a supply chain operationally.

Methodology to determine the change need and point of time in production networks by Moser (2014)

Moser (2014) introduces a methodology to identify the required change needed and what point in time for a global production network. This is realized by using a multi-objective, dynamic optimization model. The goal of the methodology is to determine for every discrete time slice of the planning horizon the optimal configuration of the production network.

Moser (2014, p. 46) explains that the approach is divided into three modules:

- Optimization module,
- Uncertainty module and
- Control module.

The optimization module consists of a model of the production network with its relevant network objects. The multi-objective target functions include quantitative and qualitative objectives to determine the solution space. These objectives include cost, lead time, quality, flexibility, coordination effort and customer proximity (Moser 2014, pp. 51–52). The uncertainty module is used to model the development of change drivers. Potential future scenarios are created which consists of a bundle of change drivers. The development of the change drivers is simulated stochastically (Moser 2014, p. 68). The control module mergers the two previous modules and conducts the simulation and optimization runs. Additionally, sensitivity analyzes are visualized (Moser 2014, p. 104).
The approach of Moser (2014) provides optimized production network configurations for every change driver development. This can be achieved as all the required elements are modeled. Concrete scenarios are not evaluated. Also, additional measures to adjust the production network transformability cannot be evaluated by the approach.

Methodology to evaluate the effects of transformability in value chain networks by Scholz-Reiter et al. (2011)

Scholz-Reiter et al. (2011) propose a methodology to analyze and evaluate the effects of transformability on logistics structures in value chain networks. To analyze the value chain network the authors divide it into three levels: network, logistic (intermediate level) and process level (Scholz-Reiter et al. 2011, p. 7). Scholz-Reiter et al. (2011, pp. 6–14) suggest a top-down approach to evaluate the transformability consisting of three steps:

1. Analyzing the existing value chain network - In the first step of the method, the setup of the value chain network is examined. The product structure is used to determine the structure of the network. To evaluate the logistic structures different operating figures such as process costs or adherence to delivery date are evaluated through the companies' specific Enterprise-Resource-Planning (ERP)-systems.
2. Change drivers and effects on logistics structures - In the second step relevant change drivers for the company are identified. Further, their effect on the logistical structures are analyzed.
3. Analyzing the effects of changeability - Further alternative logistic structures are designed to adapt the flexibility corridors of the logistic setup to the required change

drivers. These alternative logistic structures are then evaluated regarding their implementation efforts and benefits. The goal is to prepare them proactively and pull them quickly and cost-efficiently when required.

The concept shows a pragmatic approach to assess the effects of transformability on logistic structures in value chain networks. The focus lays on the logistic structures and leaves out an evaluation of the production capacities of the value chain network. Even though the method includes the effects of different change drivers on the network. Especially promising is the use of concrete operating figures to evaluate the effects.

Methodology to evaluate the flexibility of Supply Chains by Singer (2012)

Singer (2012) presents a methodology to integrate flexibility requirements in supply chain risk management. One of the goals of the methodology is to suggest an approach to evaluate the current flexibility of a supply chain.
Singer (2012, p. 150) explains that the methodology consists of five steps which also can be operated separately:

1. Approach to determine uncertainties and their potential damages,
2. Template to create flexibility profiles,
3. Catalog with measures and questions,
4. Approach to evaluate and select measures and
5. Monitoring of flexibility to supervise the measures.

The steps are embedded in an overall framework to implement the measures in a company. As the topic of this thesis is the measurement of agility, the second step of method will be discussed in detail. The flexibility of the supply chain is evaluated using flexibility profiles. The flexibility concept is divided using a process view and the following flexibility dimensions are evaluated: operative, logistic, sourcing, organization, information system and market flexibility. Each of these dimensions, except organization, has to be evaluated in terms of: change, capacity adjustment, time and cancellation flexibility. The flexibility potential and its corresponding requirement for each dimension are evaluated using a five-step qualitative scale. The information for the scale are collected by interviews with corresponding managers. Specific questions to use during the interview are provided. Figure 3.5 shows an example result of flexibility profiles. The overall result of the profiles is a spider chart illustrating for each dimension the fulfillment or lack of the required flexibility (Singer 2012, pp. 153–156).

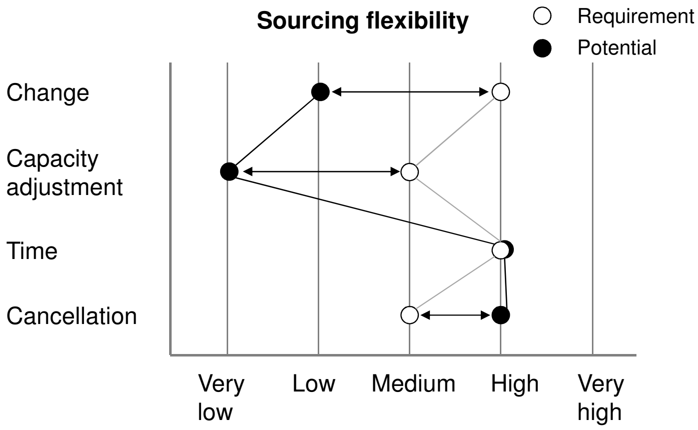

Figure 3.5: Example of a flexibility profile for sourcing flexibility, translated from (Singer 2012, p. 155).

Part of the third step is a measure catalog. It contains a collection of roughly 140 specific measures to increase flexibility in logistic, sourcing, organization, information system and market flexibility, collected from literature and interviews. Furthermore a collection of questions for companies is provided to complete the list of measures (Singer 2012, pp. 157–164).
The focus of the proposed methodology is to design the required flexibility of the supply chain. The assessment of the available flexibility is done qualitatively. Therefore it lacks a simulation-based, quantitative evaluation of the current flexibility of the supply chain. Furthermore a KPI-system to evaluate the flexibility on an operational level is not provided.

3.2.3 Conclusion

In the previous section the related work about methodologies to evaluate flexibility, transformability and agility of production was discussed. Nine of the fourteen concepts discussed evaluate the changeability of factories, the other five focus on production networks and supply chains.
Especially the methodologies to evaluate the transformability of factories, such as of Albrecht (2014), Klemke (2014), Möller (2008) or Wagner (2012), demonstrated their applicability in practice. The approaches provide a structured and operational support for the production management to assess the change capabilities of their production. The concepts of Tsourveloudis & Valavanis (2002) and Azevedo et al. (2012) use a qualitative approach. Therefore they can ideally be used as benchmarking efforts across different companies.

3.3 Derivation of research gap

In the following the findings of the discussion about stress test concepts as well as concepts to evaluate the changeability of a production will be summarized. The concepts are evaluated along the evaluation characteristics introduced in chapter 2.3 to ensure the newness of the research effort of this thesis. Figure 3.6 provides an overview of the assessed methodologies according to the evaluation characteristics.

Different approaches are available to realize stress tests in the financial industry. The works of Blaschke et al. (2001) and CEBS (2010) provide a structure to realize the stress tests. As shown in figure 3.6 the discussed approaches do not meet the requirements of the evaluation of the production network agility discussed in this thesis. As they are used in the financial industry, the requirements about an evaluation of the agility of a production network are not fulfilled. Additionally, they are no tool for the production management, only for banking management. Nevertheless, some characteristics can be transferred to the requirements of the agility evaluation.
Financial stress tests are characterized by a system's view. This means that the inter-dependencies of the portfolio elements are tested regarding a stressing scenario. The testing of the inter-dependencies is realized by using simulation techniques. Furthermore they use extreme scenarios to test the stability of a financial portfolio. They are derived from historical events and the financial product portfolio is tested on how it would react with its current structure on such events. A quantitative approach is used to evaluate the risks that a portfolio of financial products could affect. This requires a detailed model of all the included elements and factors such as macro-economic values. The result of a stress test is a quantification of the value-at-stake. It quantifies how much money a bank could loose when the extreme scenario would affect the portfolio under investigation.
Besides banking stress tests, there are further stress tests available in other industries. The focus of the stress test provided by Jain & Leong (2005) relies on the testing of a supply chain according to demand fluctuations. A quantitative agility evaluation of a production network is not its objective.
The industry stress tests for business models and for purchasing suggested by Wildemann (2015*b*) and Wildemann (2015*a*) operate on a strategic level. The structured approaches can be used to measure how fast a company can react to changes in the market. Both focus on a qualitative evaluation of the company resilience. A quantitative and holistic evaluation of agility, including the evaluation of the economic opportunities of agility, for example additional EBIT, is not part of the concept. Additionally the suggested approaches consequently are not derived from banking stress tests with a focus on the operational level of a production.
As figure 3.6 indicates, there is currently only one stress test approach available to assess the agility of a production network holistically. Therefore the work at hand transfers the

		Evaluation characteristics						
		Holistic and quantitative evaluation of agility	Production network with focal company	Stress test based approach	Tool for production management	Evaluation of inter-dependencies	Identification of improvement areas	Practicality in different industries
Stress test concepts	**In finance industry**							
	CEBS, 2010 and Blaschke, 2001	○	○	●	○	●	●	○
	In other industries							
	Jain and Leong, 2005	◑	◑	●	●	○	●	●
	Wildemann, 2015a	○	○	●	○	●	●	●
	Wildemann, 2015b	○	○	●	○	◑	●	●
Concepts to evaluate flexibility, transformability and agility	**In factories**							
	Albrecht, 2014	○	◑	○	●	●	●	◑
	Gottschalk, 2005	○	◑	○	●	●	○	●
	Heger, 2007	○	○	○	◑	○	◑	●
	Klemke, 2014	○	○	○	●	◑	●	●
	Möller, 2008	○	○	○	◑	○	◑	●
	Tsourveloudis et al., 2002	◑	○	○	○	○	◑	●
	Wagner, 2012	○	◑	○	●	◑	●	●
	Wemhöner, 2006	○	○	○	●	◑	●	◑
	Witte, 2004	○	○	○	●	○	○	●
	In production networks and supply chains							
	Azevedo, 2012	◑	◑	○	○	○	◑	●
	Lin, 2006	◑	◑	○	○	○	◑	●
	Moser, 2014	◑	●	○	●	●	○	●
	Schol-Reiter et al., 2011	◑	◑	○	●	○	◑	●
	Singer, 2012	○	◑	○	○	○	◑	●

○ - not fulfilled ◑ - partially fulfilled ● - completely fulfilled

Figure 3.6: Assessment of stress test approaches and concepts to evaluate flexibility, transformability and agility according to the evaluation characteristics.

stress test logic from the finance industry to the production environment. This enables an assessment of how agile a production network is set up to react on external shocks. It needs to be assessed which characteristics of the financial stress test can be used to create an agility stress test.

None of the concepts to evaluate flexibility, transformability or agility that have been assessed completely fulfill the evaluation characteristics that ensure the newness of the research effort. Only the concept of Azevedo et al. (2012) provides a holistic agility evaluation. All others either focus on flexibility or transformability or evaluate agility on a qualitative level. The concept of Moser (2014) is the only one that takes a production network into account. The majority of the approaches focus on a the evaluation of a factory. The stress test concept is used by none of the analyzed approaches. Most of the approaches are a tool for production management. They provide a structured process which helps production management to assess its changeability capabilities. The concepts of Azevedo et al. (2012), Tsourveloudis & Valavanis (2002) and Singer (2012) use a qualitative evaluation which is more helpful for benchmarking efforts across different companies.

Only the concepts of Albrecht (2014), Gottschalk (2005) and Moser (2014) evaluate the inter-dependencies of system elements. Whereas Albrecht (2014) simulates the material flow in a factory with a DES-model, Gottschalk (2005) relies on time-capacity-diagrams to assess the impact of different changeability measures. Moser (2014) uses a multi-objective, dynamic optimization model to evaluate different changeability measures.

Most of the analyzed concepts identify areas where the changeability of factories, production networks or supply chains can be improved. They can be applied within different industries and production types. Only the concepts of Albrecht (2014) and (Wemhöner 2006, p. 195) are focused on the medical devices and automotive industry.

It becomes clear that a methodology that fulfills the requirements articulated in chapter 1.3 is currently not available. In fact, there is no methodology available that takes a production network into consideration, uses the stress test concept and provides operational KPIs to holistically evaluate the agility. Therefore the research gap could be identified which will be filled in the following by the development of a methodology.

4 Methodology conception

In this chapter, a methodology will be proposed to answer the main research question stated in chapter 1.3. The overall objective of the methodology is to evaluate the agility of a production network by means of a stress test approach.
In section 4.1 definitions of basic concepts are introduced. These definitions are required as a foundation for the methodology developed in this thesis. Section 4.2 provides the assumptions necessary to set the frame for the application of the methodology. In section 4.3 the main idea of the methodology is explained. Section 4.4 gives an overview over the major methodology steps to evaluate the agility of a production network. The methodology is outlined in detail in the next chapter 5.

4.1 Basic definitions

To answer the research question identified in chapter 1.3 and to fulfill the requirements on the methodology introduced in chapter 2.3, several basic concepts are introduced. These concepts form the theoretical framework for the methodology which will be developed in this thesis.
A literature review was conducted about attributes which characterize agility of a production company. The results are used to extract the main agility characteristics explained in section 4.1.1. Based on these characteristics, the definition of agility in manufacturing used in this work is introduced in section 4.1.2. Section 4.1.3 explains how the stress test approach, explained in chapter 3.1, has to be adjusted to evaluate the agility of production networks.

4.1.1 Agility characteristics

Chapter 2.2.3 showed the concept of agility has recently been studied by researchers such as Kidd, Gunasekaran and Ben Naylor. It will be relied on their work in order to specify the agility characteristics and to gain the necessary understanding of the agility concept employed in the work on hand, in particular with respect to the manufacturing domain. This is also required to answer the sub-research question formulated in section 1.3 about

the definition of agility in manufacturing.
In the following the results of a literature study about the main characteristics mentioned by different agility definitions are introduced. Parts of this literature study were recently published in Wiltsche et al. (2016).

Approach to analyze agility characteristics Deep research about the agility concept has been pursued since the beginning of the 1990's (Wiltsche et al. 2016, p. 1). Positioning the agility concept of this thesis in the field of agility research and its available definitions deserve some scrutiny. The idea is to examine different agility definitions regarding their core characteristics. These insights enable the identification of the agility characteristics which are most commonly employed. These characteristics are condensed to come up with an own agility definition in section 4.1.2. This synthetic agility definition ensures a rather close connection to the corresponding body of literature.

Research methodology By means of a literature review the main characteristics of the available agility definitions were analyzed. The review was conducted in the period between February and April 2014. The search for articles and publications about the agility concept included the following online portals:

- Google Scholar[5]
- ScienceDirect[6]
- Scopus[7]

These online portals were selected as they are well-known publication databases, include a broad variety of printed as well as electronically published writings of which the author had access to. To identify the publications containing definitions of agility, the following search terms were used:

- Agility,
- Agile manufacturing and
- Agile production.

In total 35 publications were collected with each one containing one definition of agility. These definitions were examined according to the characteristics used to describe the agility concept. To render the agility characteristics employed in different definitions and to identify the most relevant ones, the identified characteristics needed to be categorized.

[5]http://scholar.google.com/
[6]http://www.sciencedirect.com/
[7]http://www.scopus.com/

Collected attributes	Agility characteristics
Speed, rapidity, quickness	1 Speed
Flexibility, reconfigurability	2 Flexibility
Profitability, prosperity, effectiveness	3 Profitability
Pro-activity, take opportunity	4 Pro-activity
Customer-orientation	5 Customer-orientation
Innovation, developing new concepts	6 Innovation

Table 4.1: Mapping of attributes to the key agility characteristics

Therefore the definitions were analyzed according to the used keywords describing agility. Different keywords were assigned to specific 'attributes' which were common across different definitions. By doing so, one agility characteristic described in different definitions using different key words could be identified as the same agility characteristic. To limit the number of used attributes, attributes describing the same characteristic were summarized to agility characteristics. All of the examined agility definitions contained several agility characteristics. By doing so, the number of core agility characteristics could be limited. Table 4.1 shows which attributes were summarized to the agility characteristics.

A detailed overview over the collected agility definitions and their categorized characteristics is provided in table A in the appendix of this work.

Agility characteristics Figure 4.1 illustrates the distribution of the identified agility characteristics of the literature review. In total six agility characteristics could be identified in the 35 analyzed agility definitions. The agility characteristics "flexibility", "profitability", "speed" and "pro-activity" were mentioned in over 50 per cent of the investigated agility definitions. The two characteristics "quality" and "innovation" on the other hand were mentioned by a third of the reviewed articles or less.
The major objective of this work is to develop a methodology to evaluate agility which then may be used as a yardstick by the production management. Therefore the defined agility definition should be applicable in practice. This requirement naturally constrains the number of the agility characteristics integrated in the agility definition used throughout this work. The subsequent four agility characteristics, highlighted in gray in figure 4.1, will be integrated into the agility definition used in this thesis:

- Flexibility,
- Profitability,
- Speed and
- Pro-activity.

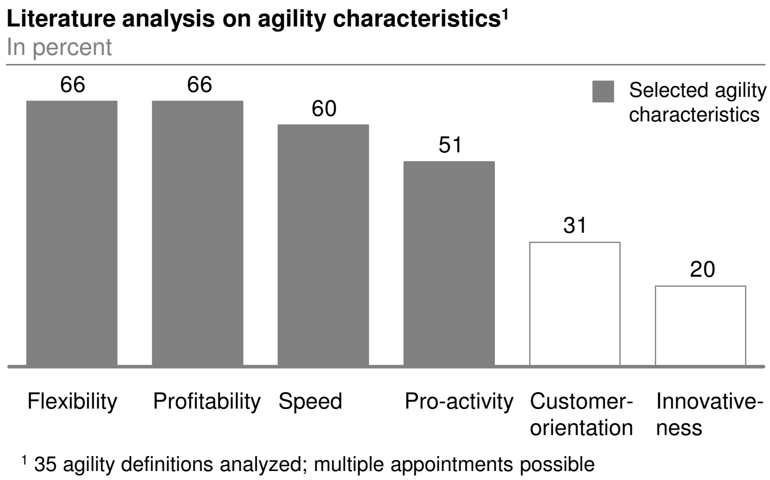

Figure 4.1: Results of the literature review about the main characteristics of the analyzed agility definitions.

In the following each one of these four agility characteristics will be introduced in detail. By doing so, their meaning and understanding throughout this thesis will be explained.

Capacity flexibility Yusuf et al. (1999) integrate flexibility as one of the six competitive bases which define the competitive foundations of agility (Yusuf et al. 1999, p. 37). It means that a company and its production requires to be flexible to contribute to its agility. Sharp et al. (1999) points out that an agile manufacturer has to be flexible as well as being lean and also be able to respond quickly to changing situations (Sharp et al. 1999, p. 159).

Sherehiy et al. (2007) focus mainly on the organization of a company which needs to be flexible in the agility concept (Sherehiy et al. 2007, p. 459). Flexible organization means in this context that the organization needs to be set up the way that it can react to the changing situations which a company faces. In their opinion, this characteristic contributes to an increased agility of a company.

As discussed in section 2.2.1, "flexibility" can have different interpretations and understandings. For the agility definition used in this work, "flexibility" is understood as capacity flexibility.

Lödding (2008) defines capacity flexibility as "the capability of a production facility to adjust its capacities quickly and cost advantageously as well as to a big extent". He explains further that capacity flexibility is limited by the bottleneck in a production system. Overall capacity flexibility of an entire production facility is usually derived from the capacity flexibility of its single production stations (Lödding 2008, pp. 467–473). This implies that the capacity flexibility of a production system can only be increased if the constraints at the production system's bottleneck are released. Bottlenecks in a production system overlap and influence each other. The resulting observable phenomena's are

often analytically intractable. That is one of the reasons why a material flow simulation model will be an integrated part of the developed methodology.
Capacity flexibility in the agility definition used throughout this thesis describes the maximum or minimum amount of the available production capacity, measured as output quantity produced per time period. This measure quantifies the range of the production capacity which can be covered by the output of the production network.

Profitability Whereas flexibility focuses on the production of a company, profitability connects to its strategic and financial goals. Profitability as a characteristic of agility is mentioned by authors such as Tsourveloudis & Valavanis (2002), Zhang & Sharifi (2007) and Izadpanah & Yaghoubipoor (2012).
Tsourveloudis & Valavanis (2002) understand profitability in the context of agility of how companies can adjust to fluctuating market conditions. In their perspective agile companies use sudden changes as opportunities to increase their profits (Tsourveloudis & Valavanis 2002, p. 330). This means that a company has to apply agility measures to benefit from market opportunities which pay off by an increased profit for the company.
Zhang & Sharifi (2007) describe agility as a concept to "prosper from dynamic and continuous changes in the business environment" (Zhang & Sharifi 2007, p. 352). They suggest that the company shall "seek to provide the competitive capabilities" which are required to benefit from unexpected changes. Their understanding indicates the same objective as mentioned by Tsourveloudis & Valavanis (2002). This means, leveraging these capabilities to react faster to the changes such as unexpected strong growth or slumps in demand other than its competitors. The selection of the "competitive capabilities" needs to be assessed according to its contribution to the overall financial prosperity of the company, meaning its profitability.
Profitability as an agility characteristic implies that operational measures selected to improve the agility of a company are not only evaluated according to their cost impact. A characteristic used by the transformability concept discussed in chapter 2.2.2 by (Nyhuis et al. 2008, p. 73). The profitability characteristic in the agility context rather extends its scope. The used agility measures need to be evaluated according to their impact on the company's profitability. Managers who manage the profitability of their company or business unit are able to use the increased freedom to make decisions. Their objective to maximize the profit enable them to include the potential generation of profit into their thinking and does not limit their view on achieving specified service levels while minimizing costs (Abele 2008, pp. 276–279). Agility measures which cause additional costs in the short-term, might create benefits in the long-term. Different measures could be activated which lead to additional costs, but might be necessary as strategic moves to improve the business position of a company in the future. The payback in terms of additional profit will be in the future. Schurig et al. (2014) introduce examples of these measures from practice.

The optimization of the economic situation of a company by an improved agility will be assessed by measuring its profitability impact. The profitability is calculated as the generated EBIT impact during the evaluation period.

Speed Speed is another agility characteristic which was mentioned by approximately 60 per cent of the investigated agility definitions. In the investigated definitions, speed is explained as the capability to adjust to changing market demands and requirements in a fast way (Gunasekaran 1998, p. 1223), (Yusuf et al. 1999, p. 36) and (Brown & Bessant 2003, p. 707). The changes in customer demand can be diverse, for instance customers may demand different technologies or a higher or lower quantity of a product.
Assuming that demand fluctuations are increasing within a short time period a production company needs to react to these fluctuations by adjusting its output capacity. The agility characteristic "speed" describes how fast a production company can change its output to follow as closely as possible to the demand changes. The faster the company can adjust its production output in both directions, the more agile the company is according to this characteristic.
If a company is capable of adjusting its output capacity quicker than a competitor, the closer it comes to fulfilling real customer demand. This leads to a competitive advantage. Real customer demand means unfiltered customer orders placed by consumers from the market. The demand is not influenced by demand shaping activities such as demand smoothing or incentives for customers to buy off-peak (Waller 2004, pp. 13–15) or sales measures such as timely price differentiations or cyclical marketing activities (Krüger 2004, p. 41).
The production company and its production network need to be set up according to the speed characteristic. A required speed level which is too ambitious can lead to excessive noise in the value chain, for example by increasing inventory throughout the production network or dismissing orders from suppliers. Also the bullwhip effect in the supply chain, described as a major problem in supply chains by Alicke (2005, pp. 99–130), has to be taken into consideration. The bullwhip effect describes the reaction that demand fluctuations increase significantly from the customer upwards the logistic chain to the suppliers due to insufficient information sharing (Jammernegg et al. 2000, p. 191).
The evaluation of the speed of the capacity adjustment can be measured in units of time (for example, days, weeks or months) required to achieve a specific level of production capacity.

Pro-activity Pro-activity as an agility characteristic was mentioned by 51 per cent of the agility definitions. Yusuf et al. (1999) understand pro-activity to foresee the products a customer demands before the need arises (Yusuf et al. 1999, p. 39). This means a company proactively needs to analyze its customers and handle their needs.

McCann et al. (2009) describe agility as being “flexible and decisive in anticipating, initiating and taking advantage of opportunities and avoiding any negative consequences of change” (McCann et al. 2009, p. 45). This includes that a company constantly evaluates its market position and aims to exploit its competitive advantage. Evaluating and assessing the market requirements proactively and comparing it with its own capabilities describes the pro-activity characteristic closely.
Pro-activity in the course of this work describes the characteristic of a company to proactively deal with its changing environment. It describes the efforts inside a company to be active about the change upfront and to prepare for it.
The realization of pro-activity can be different in practice, for instance by using different future scenarios in the management process or prepare operational measures which can be activated when needed. A proactive company actively deals with potential changes and takes on market opportunities. For example, the usage and running of a stress test as explained in this work may be an example of a firm’s pro-activity.
Pro-activity as understood in this thesis is a qualitative characteristic. This means that it can not be evaluated by specific parameters. In contrast with the previous three characteristics where specific KPIs were mentioned.
Nevertheless, pro-activity is part of the agility concept. The characteristic means that a company thinks about its agility themselves without any external trigger. This can be seen by different activities a company actively starts.

4.1.2 Definition of agility in manufacturing

Based on the identified agility characteristics of the previous section an agility definition is introduced. This definition delimitates agility from flexibility and transformability discussed in chapter 2.2. Additionally, it develops the available agility definitions further and creates a common understanding of the agility concept used in the course of this thesis.
The combination of the agility characteristics identified in the previous section leads to the general definition of agility by (Schurig et al. 2014, p. 957). Their definition needs to be transferred to manufacturing and adjusted to the requirements of this work.

> Agility in manufacturing is the capability of a production company to proactively prepare for uncertainties and to react quickly to changes in order to optimize the economic situation of a company, measured by profitability, leveraging the entire production network.

As pointed out by Schurig et al. (2014), the concepts of flexibility and transformability are included into the agility concept. Therefore the agility concept can be understood as an overlapping concept which includes the existing concepts how to prepare for changes in production. Figure 4.2 illustrates how the characteristics identified in the previous section are integrated into the agility definition.

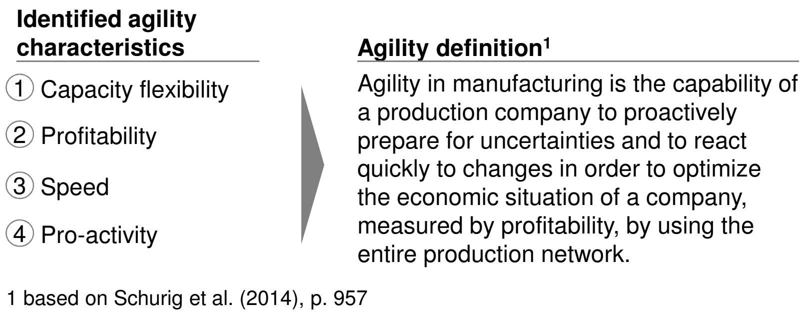

Figure 4.2: Agility characteristics included into the agility definition.

The agility characteristics which were integrated into the agility definition will be defined as the following throughout this thesis:

- Capacity flexibility describes the maximum or minimum amount of the available production capacity of the production network. It is measured as unit of output quantity per time period.
- Profitability defines the benefit a company can generate during a time period which can be short- or long-term. It is measured in monetary units.
- Speed is understood as the time it requires to adjust the output quantity of the production network from one value to another. It is expressed in time units.
- Pro-activity describes the capability of a company to evaluate its agility by itself, without any external trigger. Due to the qualitative personality of pro-activity, it will not be part of the quantitative agility evaluation.

By putting the optimization of the economic situation of a company in the middle of the agility concept it offers a unique and differentiating characteristic compared to the concepts of flexibility and transformability. It does not limit its view to the additional costs which specific measures contain to increase the agility of a company. Rather it extends the focus on the business model of a company. It therefore enables a company to think in additional perspectives to changes in its environment:

- In the identification of opportunities in case of positive changes, for instance an upturn in the economic environment or in the introduction of new, promising technologies or
- To apply necessary measures in negative situations, for example in case of economic

downturns which enable the company to adapt quicker to changes, as opposed to others.

The capturing of opportunities might require additional spending. In case of an economic upturn the extension of the available production capacities is necessary. This would lead to additional investments which need to be paid off. At the same time the increased production capacities would satisfy customer demand faster and more extensive which results in additional revenues. It therefore allows the company to use market opportunities during the economic upturn more consequently than others and gain market shares from its competitors. While limiting the perspective only on the costs which are associated with the measures to speed up an output increase, this market opportunity would potentially not be covered. However, by setting the investment in relation to the potentially additional revenue that can be gained, the decision can be made based on the overall financial situation of the company.
In the course of this work, the improvement of the economic situation of a company will be evaluated by the EBIT impact that different agility measures have. The stress test approach introduced in the following section allows to check how a company can react on different extreme scenarios that are unusual for the company. In other situations, the improvement of the economic situation of a company can be measured by an increase of market share or the optimization of the Return on Investment (ROI). The unit used to evaluate the improvement depends on the situation of a company and the goals its management is pursuing (Schurig et al. 2014, p. 957).
The introduced agility definition takes the production network into consideration. Therefore the number of potential agility measures to react on changes increases compared to when only focusing on the production inside a company or factory. This is the limitation of the transformability concept (Klemke 2014, p. 39).
This increase of potential agility measures means that operational measures can be defined for all of the production network partners. This requires an increased cooperation among these network partners. Nevertheless, it needs to be ensured that the production network is lead by the focal company and hence it drives the efforts to increase the production networks agility. Types of cooperation are possible that use contractual arrangements, such as Build-operate-transfer (BOT) solutions such as “pay-on-production”, outsourcing solutions or the usage of contract manufacturing arrangements (Rippel, Schmiester, Wandfluh & Schönsleben 2015, p. 4). Also concepts such as “Peak-Breaker-Plants” can be used where contract manufacturers take over the excess production of OEMs in a highly flexible cooperation (Breitschwerdt et al. 2011).

4.1.3 From finance industry to production networks: transfer of the stress test approach

The objective of this section is the explanation how the concept of stress tests mainly applied in the finance industry can be transferred and be used to evaluate the agility of a production network. The findings presented in chapter 3.1 are used as a basis and guideline.
The stress test approach in the context of this thesis aims to analyze the agility of the production network by exposing it to scenarios with strong demand fluctuations. The agility of the production network is quantified by using a set of specific KPIs with the goal of revealing weak points of the production networks agility. Whereas several concrete tools and methods of the stress test of the finance industry cannot directly be transferred to the production environment, its main thoughts and principles can be adapted and applied.
In chapter 3 a set of features characterizing stress tests in the finance industry were identified. In the following it is explained how these characteristics can be applied in to environment of a production network:

- **Concept of extreme scenarios:** The characteristic to use extreme scenarios to test the performance of a system was identified as the most important stress test characteristic. Using scenarios with extreme events means that significant stress is put on the system. Therefore they are called 'stressing demand scenarios' in the course of this work. One can investigate how the system would react and handle such a challenging and unusual situation. The agility of the production network should be evaluated regarding demand fluctuations. This means the stressing demand scenario needs to be defined for extreme demand fluctuations. The management of the production network gains insights about how the production network is capable to react on it from an agility perspective.

- **Usage of historical scenarios:** The idea to use historical events as reference cases can also be transferred to the developed stress test of production networks. The objective to use historical scenarios is to understand how the current setup of the system in scope would handle this concrete situation that happened in the past. By using scenarios which occurred in the past, a discussion can be avoided about how likely the occurrence of potential future scenarios are. It can be referred to the fact that the identified historical scenario occurred and that the assumption for the realization of the stress test is that to the production network in case the historic scenario would happen again.

- **Quantify the impact and value-at-stake:** The goal of the finance stress test is to quantify the risk and the financial consequences of specific events. This characteristic can also be transferred to the agility stress test of the production network. The agility stress test comparably evaluates financially and in terms of profitability as well as how agile the production network is set-up. It quantifies the opportunities in terms of additional profit as well as risks, calculated by additional losses which can occur in the course of the stress test scenario. The management of the production network receives a quantification of the profitability impact of different agility setups regarding the specific stress test scenario.

- **Simulate the system and its components:** The stress test in the finance industry uses simulations of portfolios consisting of financial products. The simulations evaluate their behavior according to the different scenarios. A simulation is a helpful and powerful tool to gain insights over the behavior of complex systems and the inter-dependencies of their elements and components (Robinson 2003, p. 4). It can be used to create transparency about the performance of a system as well as its weak points. Röhrs (2003, pp. 13–14) states that a production network can be defined as a system as well. Therefore a simulation is also a powerful tool to evaluate the performance and behavior of production networks.

These characteristics of the finance stress test will be integrated into the stress test methodology to evaluate the agility of a production network.

4.2 Application area and assumptions

The objective of this section is to set the frame for the application of the developed methodology. This is done by defining the application area as we as the assumptions for the developed methodology.

Application area The application focus of the developed methodology are production networks with a leading focal company. The production network consists of production sites of different companies where assembly and processing steps take place. The production sites of the network can be either part of the focal company or belong to suppliers. Production processes are seen as the manufacturing of parts and sub-assemblies and their subsequent assembly (Warnecke 1993, p. 1). The production network is lead and steered by the focal company. This means that material flows along the value chain downwards from suppliers to the final assembly at the focal company. The information flows the opposite direction from the final assembly upwards the value chain to the suppliers. The focal company receives orders from its customers. The methodology takes the available production capacities of tier-1 suppliers into consideration. Production capacities at the suppliers in lower tiers are not in the focus of the methodology. For all of the mentioned partners of the production network the related logistic activities, e.g. transportation and storing activities, are considered as well. Figure 4.3 shows the production network in scope of the methodology.

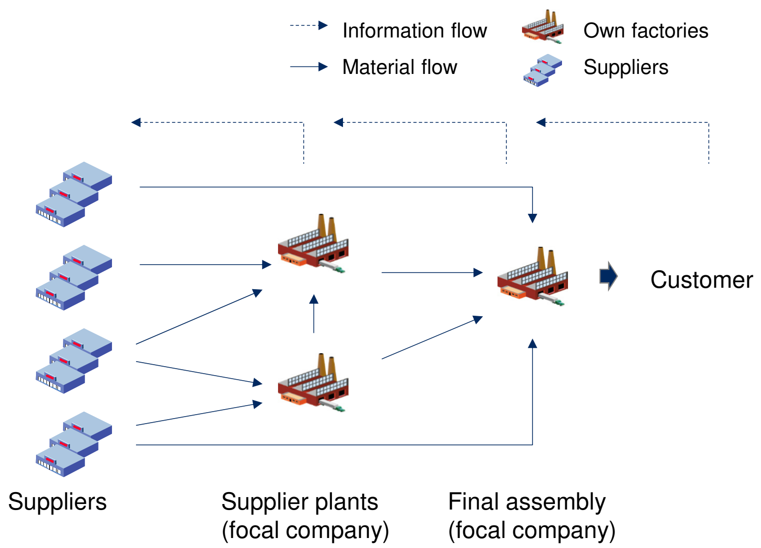

Figure 4.3: Scope of the production network.

Assumptions General assumptions for the methodology need to be defined in order to ensure a purposeful and successful execution of the method. Their usage on the other hand limits the validity of the results. In the following assumptions are summarized:

- A1: The production network represents the value creation chain for one single product. In addition to the focal company it consists of internal and external supplier sites. The suppliers are integrated up to tier-1. The reason is that a focal company usually has deep relations and cooperation with its tier-one suppliers, including well-established information exchange.
- A2: The focal company leads the production network. Therefore its management initiates and drives the efforts to evaluate the agility of the production network in scope using the stress test approach.
- A3: Demand fluctuations from the market affect the company directly with a limited forecast period of only one month. No marketing measures to level and influence the demand, for example, by applying demand shaping activities, are employed.
- A4: The production network is simulated using a simulation engine consisting of a material flow model and a profitability model. The simulation engine uses a top down view and integrates the main production steps of the network partners. This means that agility measures to react on changes are reflected on a general level. A detailed investigation of the measures is not done.

- A5: The stressing course of demand in a strong growth scenario leads to the situation that every product that is produced can be sold to the customer. This assumption increases the pressure on the supply chain orientated towards the customer, for example, delivery logistics or warehouses. As the methodology focuses on the production side of the supply chain, the implications of the stressing demand scenario on the customer side are not evaluated.

4.3 Solution proposal

This section provides an overview over the developed methodology. The methodology is the answer to the main research question articulated in chapter 1.3. A first outline of the methodology was published by the author in Schurig & Ramsauer (2015).
The methodology developed in this work aims to fulfill the following functions:

- Evaluate the agility of a production network in the current state,
- Identify measures to improve the agility of a production network (if needed) and
- Evaluate the agility of a production network in the improved state.

The overall idea of the methodology is to evaluate the agility of production networks by testing their performance according to challenging demand scenarios consisting of strong demand fluctuations. This is realized by defining stressing demand scenarios derived from historical demand data of the product in scope.
The resulting performance of the production network setups are evaluated along the following three agility characteristics:

- adjustable capacity,
- speed to adjust capacity and
- profitability.

The fourth agility characteristic pro-activity is intrinsically taken as given as the company actively realizes an evaluation of its agility. The agility of the production network is simulated using a material flow model and a profitability model.
The approach is inspired by the stress test logic which is currently used in the financial industry as explained in chapter 3.1. The idea is to analyze the implications of crises or catastrophes on a system and how it would react to them. The methodology developed in this thesis takes this idea as a guiding thought by using demand patterns from historical crises. Examples are macro-economic crises such as the first oil crisis in 1973 or the financial crisis between 2008 and 2010. In particular this means that a demand scenario

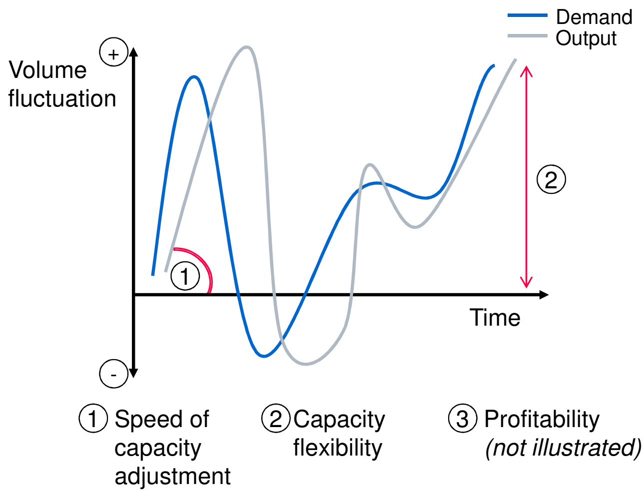

Figure 4.4: Schematic diagram of the demand and output curves of a production network and explanation of agility characteristics, adapted from (Rabitsch et al. 2015, p. 47).

is characterized as stressing for the production network. It means that the scenario is characterized by strong, short-term changes in demand. These demand scenarios are derived from two sources: One are historical demand courses of the product in scope. In case, there is no historical demand data for this product available, comparable sources can be used, for example from comparable product from the company or industry. The methodology applies the resulting fluctuations of the product demand to the production network.
The methodology evaluates how close the output of the production network gets to the demand curve of the stress test scenario. The main objective is to reduce the difference between the demand and output curves. This can be achieved by a fast and appropriate reaction of the output quantity of the production network. The agility characteristics which are part of the definition enable the reaction. The relation between the output and input curves as well as the integrated agility characteristics is illustrated in figure 4.4. The objective of the methodology is to evaluate how close the production network is capable to react on the demand fluctuations in two states for the production network: in its current state as well as in an improved state.
It is expected that the inertia of the production network hinders its focal company to adjust the output quantity closely to the demand fluctuation. The hypothesis to overcome this inertia is the increase of the agility of the production network. This can be achieved by using different operational agility measures throughout the production network.

If the demand fluctuation of the scenario cannot be fulfilled with the current agility of the production network, further production network setups can be defined, tested and evaluated using the simulation engine. This aims to improve and adjust the agility of the production network to the needs defined by the management of the focal company.
The result of the methodology is a set of production network setups which are evaluated

regarding their agility. The identified production network setups can be used by the management of the production network to improve and adjust, if needed, the agility of the production network.

4.4 Structure of the methodology

The methodology to evaluate the agility of the production network setups consists of four steps. Figure 4.5 provides an overview of the steps which will be summarized in the following. Chapter 5 contributes the detailed description of the methodology.

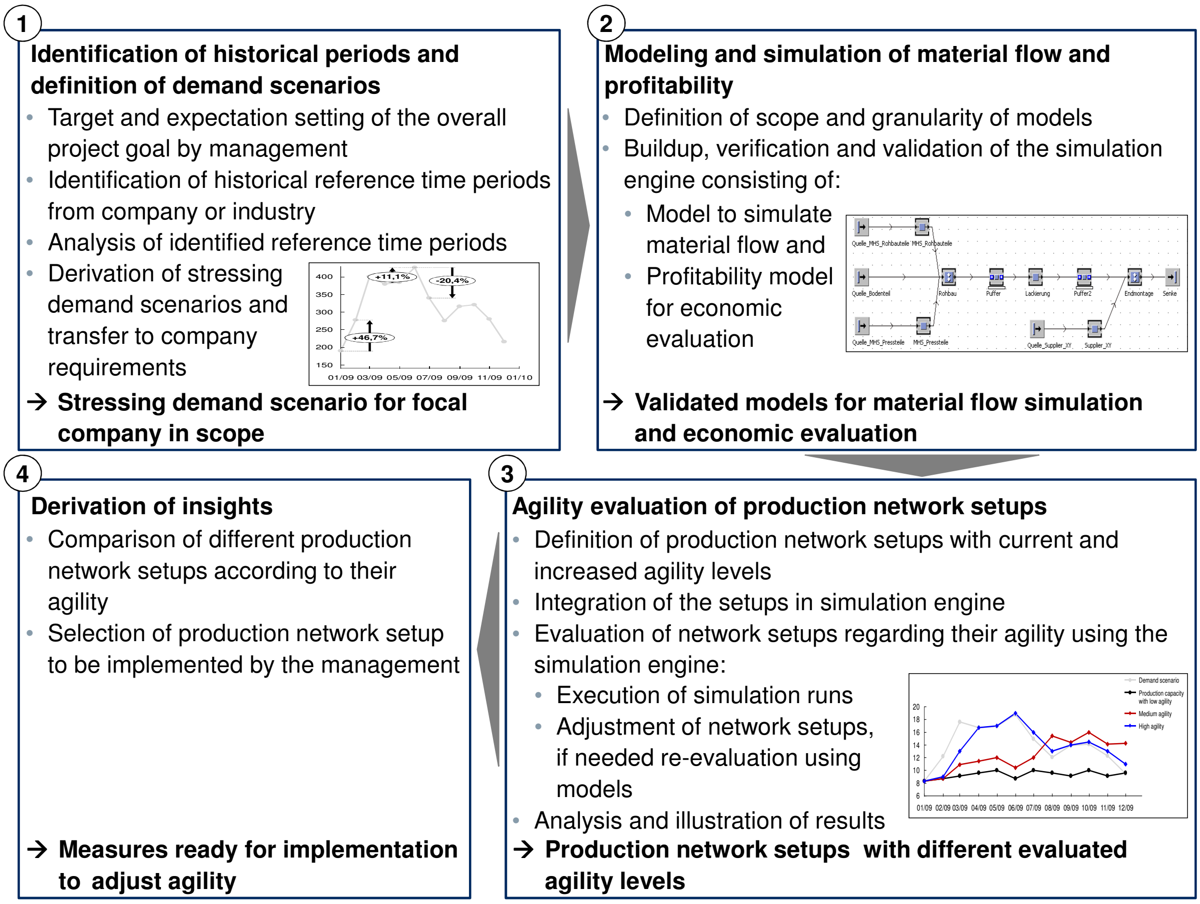

Figure 4.5: The structure of the created approach in overview.

1. Identification of historical periods and definition of demand scenarios The methodology starts with the definition of the project goals by the production management of the focal company. Thereafter time frames in the past are identified when the company or the industry it operates in experienced strong demand fluctuations. The objective is to identify times with strong demand increases or declines within a short time, often results of macro-economic or financial markets shocks. These time frames are called "reference

time periods". The identified periods need to be analyzed regarding their demand patterns such as fluctuations over a time period and fluctuation magnitude. The results of the analyzes are relative demand fluctuations between time periods, for example, between weeks. These identified demand patterns are then transferred to the production volume dimensions of the production network. This is done by calculating the corresponding production volumes of the production network. To achieve this goal the relative fluctuations between time periods are applied to a baseline production volume of the production network.
The result of this methodological step are stressing demand scenarios for the production network. The stressing demand scenarios are hypothetical for the company, but are based on historical courses. They can reflect strong short-term demand fluctuations for both demand slumps and booms.

2. Modeling and simulation of material flow and profitability After the derivation of the stressing demand scenarios, two simulation models have to be built up: a model for simulating the material flow in the production networks and a model to simulate the profitability impact. These two models are combined to a "simulation engine" which enables the evaluation of a production network's agility by simulating its performance according to the three agility characteristics adjustable capacity, speed to adjust capacity and profitability.
This methodological step initiates the definition of the observation area. The partners of the production network are selected that will be within the scope of the agility evaluation. This results in setting the system boundaries of the production network in scope. Also the product or product family for which the evaluation should be realized has to be defined. Following, the required process data has to be collected for the production network in scope. It is used to construct and parameterize the material flow simulation model of the production network. With the collected data, a conceptual model of the production network is created. This conceptual material flow model is created using the value stream methodology aiming to collect all of the required process and operations data. With the conceptual model available, the material flow model in the simulation software is created. For the simulation model the DES is used. The whole process flow of the production network within the system boundaries as well as with the defined level of detail is integrated into the material flow model in the simulation software. The demand scenario has to be integrated into the model as well. Finally, the created software model needs to be verified and validated.
A profitability model is created to evaluate the economic performance of the production network setups. They are evaluated according to their EBIT impact. For that, the corresponding revenue as well as the costs for the agility measures are integrated.
The results of this methodological step are two validated production network models. They are combined to the "simulation engine". The simulation engine is able to evaluate

the agility performance of the production network setups by simulating their material flow and profitability impact. The production network setups consist of a set of operational measures to influence the agility of the production network.

3. Agility evaluation of production network setups The methodology step aims to evaluate different production network setups according to their agility. Based on the stressing demand scenarios production network setups with different agility levels are derived. The simulation engine is used to evaluate the agility of the production network setups.

This methodology step consists of four sub-steps. During the first sub-step different operational measures are combined to production network setups with different agility levels. Within the second sub-step these setups are integrated into the simulation engine. In the course of the third sub-step the simulation of the production network setups are realized. The fourth evaluates their agility along the agility characteristics and illustrates the results. The four steps are iterative which means that they can be repeated until the required agility levels are achieved.

The overarching attempt of the production network setups is to fulfill the derived demand scenario as close as possible. This means that the output curve of the production network should be as close as possible to the stressing demand curve. This can be accomplished by minimizing the reaction time of adjusting the output curve to the demand curve.

To realize this task, different production network setups are defined. These setups are simulated and evaluated with respect to their impact on the agility of the production network.

The definition of production network setups with different agility levels is realized in an iterative process while experimenting with the simulation engine as mentioned above. In the course of the experimentation both new agility measures are defined and already existing ones are adapted. The results of the simulation and evaluation runs are analyzed, compared and illustrated according to their agility. Agility curves are used to compare the course of the stressing demand with the resulting output quantity of the production network setups. Especially the connection between the amount of the adjustable production and its adjustment speed as well as the corresponding profitability are analyzed and assessed.

The results of this step are simulated and economically evaluated production network setups with different agility levels. These evaluated setups are used as an input for management discussions regarding what agility level of the production network has to be implemented.

4. Derivation of insights The fourth step of the created methodology deals with the discussion and selection of these operational measures which will be implemented in order to increase the agility of the production network. For this step the evaluated production network setups need to be illustrated for the production management. The result of this step is a list of selected agility measures which should be implemented to adjust the agility of the production network.

5 Methodology to evaluate the agility of a production network

In this chapter the methodology to evaluate the current agility of a production network by using a stress test approach is explained. The methodology consists of four steps, figure 4.5 provides an overview. It is the answer to the main research question regarding the design of a methodology to evaluate the agility of a production network.
Section 5.1 explains how stressing demand scenarios are identified to test the agility of the production network. A description of how the models for the material flow and profitability simulation are built up is given in section 5.2. The third section 5.3 of this chapter discusses the agility evaluation of the created production network setups. The fourth methodology step in section 5.4 focuses on the generation of insights and derivation of implementation tasks to adjust the agility of the production network.

5.1 Identification of historical periods and definition of demand scenarios

The evaluation of the production network agility needs to be realized in a dedicated project. Therefore the definition of the goals, scope and setup of the project is explained within the following. Thereafter it is described how historical reference time periods with economic crisis or booms are identified. It is described how these time periods are analyzed according to their demand fluctuations. For time periods with strong demand fluctuations a stressing demand scenario is derived and transferred to the requirements of the company that realizes the stress test effort. The result of this methodology step are stressing demand scenarios which consist of order courses for the focal company in scope.

5.1.1 Project setup

The application of the methodology is a unique effort. Therefore it should be realized in a project setup. A project is defined as a time limited, unique and complex task. It is

characterized by being novel, goal-orientated, clearly defined, complex and dynamic, interdisciplinary and relevant (Patzak & Rattay 2009, pp. 19–20). All of these characteristics are fulfilled by the agility evaluation effort on hand. Therefore it should be realized in a project setting.
To fulfill these characteristics Patzak & Rattay (2009) recommend to ensure that the following four pre-conditions are defined before the project starts:

1. Definition of a project owner and sponsor,
2. Formulation of project goals and expected results of the project,
3. Definition of the project team members and stakeholder analysis,
4. Set up of the project governance and creation of project plan.

For the realization of the agility evaluation project using the developed methodology means that these pre-conditions need to be fulfilled in order to begin. The first pre-condition of the project owner and sponsor is usually given naturally as the top management of the focal company initiates the agility evaluation effort. The attention of top management is required to receive the necessary attention inside the focal company, and also when discussing issues with the production network partners. Also the reach of the impact of potential measures derived based on the agility evaluation demand attention from the top management. So usually the sponsors should be the Chief Operating Officer (COO) or even the CEO of the focal company. One of them is required to be the project owner.
The second pre-condition about the project goals is directly specified by the project owners. During a kick-off meeting with them and the project team the goals and expected results of the agility evaluation should be formulated clearly. The project manager has to collect the different goals, evaluate if they are realistic and ensure that they are aligned. It is helpful to write them down to create the commitment of the project team and sponsors.
The project team should consist of experienced employees with a production or supply chain background from the focal company as they drive the effort. They should have access to specified representatives from the production planning, production management, sourcing and supply chain management departments of the focal company. Towards the production network they require connection to representatives of the sales and production management department of the suppliers. These representatives should be experienced employees with a deep understanding of their fields of activity. In the case of detailed questions that cannot be answered by them, additional experts from the mentioned as well as from adjacent departments, for example maintenance or logistic departments, should be contacted at short notice.
The approach requires the interaction with different stakeholders. In addition to representatives of the production factories of the focal company, also suppliers and service

providers such as logistic and transport providers need to be integrated into the evaluation of the agility of the production network as well. It is required to have a stakeholder management as different stakeholders have different expectations and interests about the project.
It is recommended to define a project governance consisting of meetings and steering committees with the required sponsors, team members and stakeholders. A clear and appropriate structure should be put in place. Furthermore, a project plan for the realization of the effort needs to be defined. This enables an efficient usage of the available resources. Different publications are available with detailed information about setting up projects such as Meredith (2008) and Burghardt (2012) that can be consulted.

5.1.2 Derivation of demand scenarios

As described in section 4.1.3, one of characteristics of the agility stress test is the usage of extreme scenarios to test a system according to its stability. These extreme scenarios are derived from historical events. Therefore the reference time periods for the creation of the demand scenarios are derived from historical time frames during which strong demand fluctuations could be observed. The reference time periods need to be analyzed regarding their demand patterns in order to identify those time frames with strong demand fluctuations. At the end of this step the stressing demand scenarios for the agility stress test are derived.
Strong demand fluctuations in this context are defined as significant changes in demand during a relatively short time. The specifications of these characteristic depend on the circumstances when the stress test is realized.

Identification of historical reference time periods

The goal of this methodological step is to identify and select reference time periods from the past which are characterized by strong demand fluctuations. These periods are used as a reference to derive the demand scenario for the agility stress test.
In the banking industry, a selection of different time periods is available during which economic crises and financial shocks took place. These time periods are regularly used as reference examples to create the banking stress tests BIS (2001). Following Ludwig et al. (2010, p. 65) these time periods of economic crises and financial shocks include:

- “Black Monday” in 1987 which refers to Monday, October 19th 1987, and the following days when stock markets around the world collapsed,
- The Asia crisis in 1997/98 with impact on the global stock and bond markets as well as exchange rates,

- The Terror attacks of 9/11 in 2001 which had significant impact on the global financial markets and
- The Financial crisis between 2008 and 2009 with significant impact on the global economy.

These crises and shocks had a significant impact on the real economy resulting in effects such as an increase in unemployment rates, slow down of economic growth, increase of credit default rates or demand fluctuations for goods and services (Ludwig et al. 2010, p. 75). All of these consequences result in increased risk types such as credit, market or liquidity risk for the banks and their portfolio (CEBS 2010, p. 4). Therefore the hypothesis of finance stress tests is that historic time periods with extreme events result in strong fluctuations in the risk developments (Ludwig et al. 2010, p. 75). This hypothesis will be transferred to the agility stress test.

For the developed agility stress test methodology this means that time periods with economic crises and booms as well as financial shocks and increases can be used as reference time periods. The hypothesis is that during these times the input factors that put stress on the production network fluctuate as well. As the methodology focuses on the investigation of the impact of demand changes the historic reference time periods have to be analyzed according to their demand fluctuations.

The selection of the specific reference time period is influenced by many factors. Factors include decisions about the specific crisis or booms used as a reference, the length of the reference time period or its geographic focus.

What specific crisis or boom time will be selected depends on the goal of the agility evaluation set at the beginning of the project. Depending on whether the company wants to assess their agility to react to economic down turns or economic growths. In case of economic downturns this would mean using an economic crisis as a reference, for example the Financial crisis between 2008 and 2009. In the case it wants to evaluate their agility to react on economic growth, an example could be the recovery after the Financial crisis between 2009 and 2010. Especially in the German car and machinery industry strong growth could be observed (VDA 2015), (VDMA 2013, p. 10).

The length of the time frame which should be considered depends on the industry the company operates in. The requirement on the period is to represent a period with significant changes in demand which is challenging for the focal company. Furthermore the time period should be long enough that the demand change cannot be covered exclusively by operational short term measures such as overtime or the usage of contractual workers. It needs to be ensured that the management is required to include operational long-term measures to adjust the output. Additionally, the time period should not be too long to not start a discussion around the life-cycle of the industry and the product. Further, the length of the period can be oriented at machine-life-cycle or a machine's depreciation period. Another possibility could be the inspiration by a forecast which is based

on sales projections, assumptions or expectations of the sales and marketing department (Schönsleben 2011, pp. 467–469). As an example, for the automotive industry, a period of twelve months appeared to be practical.
Additionally, the geographic focus which underlines the demand data can be different as well. If required, global data could be used. Furthermore, regional focuses of the data can be selected. It could be reasonable that demand data from a specific, very relevant country with high demand volatility is selected.

Pattern analysis and selection of reference time periods

For the reference time periods identified in previous step, the demand data has to be analyzed according to its patterns. Since the hypothesis is that economic booms or crises result in strong changes in demand, these patterns have to be identified. At the end of this step, based on the demand pattern analyzes this reference time period is selected which will be used to create the stressing demand scenario.
The required data for understanding the demand fluctuations of a product as a result of economic crises or financial shocks can have two sources: the first is the focal company itself. If it possesses a demand history of the product in scope ranging deep into the past, this data can be used to understand the magnitude and characteristic of the demand fluctuations during the reference time periods. The second source could be official demand data of comparable products. Examples could be data about the car registrations in specific countries for the automotive industry or indexes about received orders for the machinery industry. Data providers for these two cases are, for instance, the European Automobile Manufacturers' Association (ACEA) for the car registrations. For the machinery industry the "New orders index" provided by Statistics Austria or the "Industrial production index" published by EuroStat can be used.
The available demand data has to be investigated according to their patterns. Schönsleben (2011, p. 473) defines a demand pattern as an attempt "to model the demand by deriving a graph around which the values scatter as few as possible". These patterns can be used for forecast methods which create predictions of demand based on the historical data patterns. Wagner (2012, p. 26) distinguishes between three types of demand patterns. Their courses are illustrated in 5.1:

- Changes in demand, characterized as a market shift with a one-time change of the market constellations. They can be separated into:
  - Discontinuous shifts occur suddenly. They are usually unpredictable. An example is the income of a large order.
  - Continuous shifts are constantly moving into one direction (de- or increasing) following a specific form (linear or nonlinear) over a year. They are also known

as “trends”.

- Demand fluctuations are defined as continuous and repeating changes of the market constellation in uneven forms. Based on their recurrence they can be separated into:
  - Nonlinear courses with a turning point. These are fluctuations that occur irregularly.
  - Seasonal courses are characterized by regular cycles.
- No changes in demand.

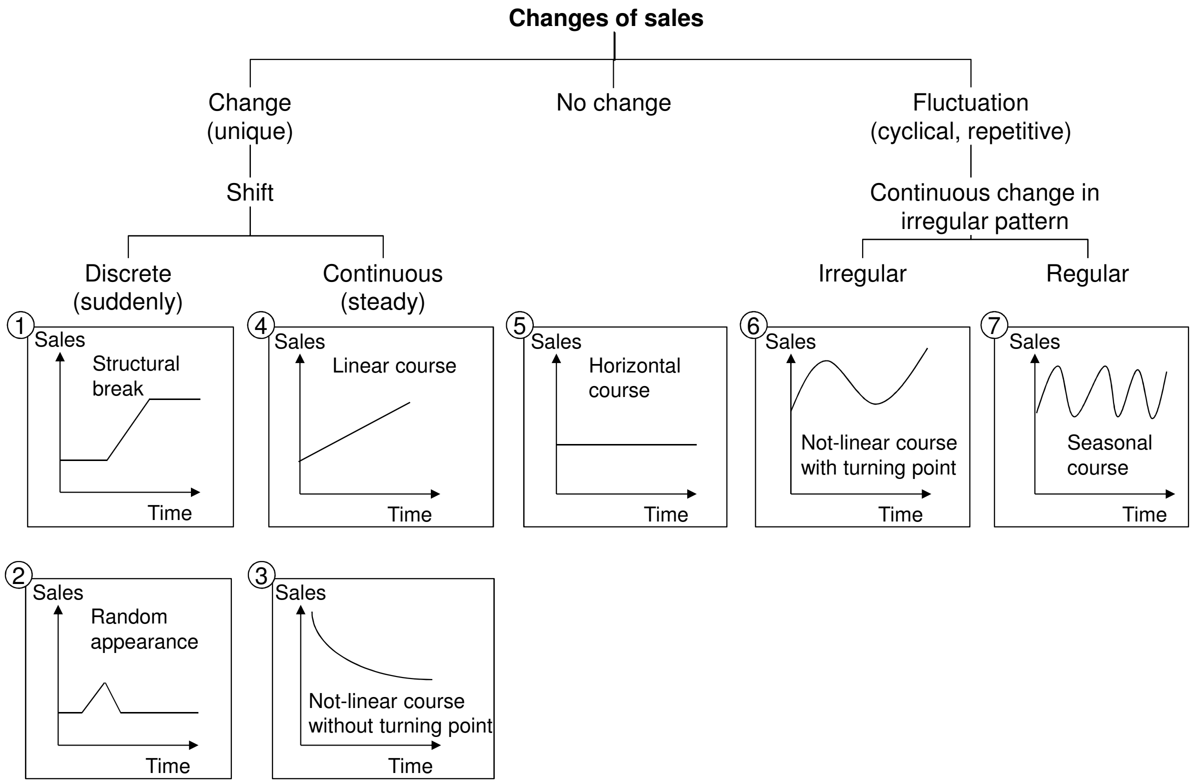

Figure 5.1: Characterization of sales patterns, adapted from (Wagner 2012, p. 26) and (Krüger 2004, 18–21).

Wiendahl (1986, p. 26) explains that the patterns one to three illustrated in figure 5.1 can be handled by intuitive predictions or by reacting after their appearance. The patterns four to seven can be forecasted using different mathematical forecasting methods. Mertens & Rässler (2012) as well as Schönsleben (2011) suggest a broad range of mathematical forecasting methodologies.
The developed methodology focuses on demand patterns that cannot be predicted. These patterns have to be repeating changes in uneven forms. Therefore, the demand data of the reference time periods has to be analyzed according to demand fluctuations of a nonlinear course with turning points. This pattern is marked with number six in figure 5.1. This

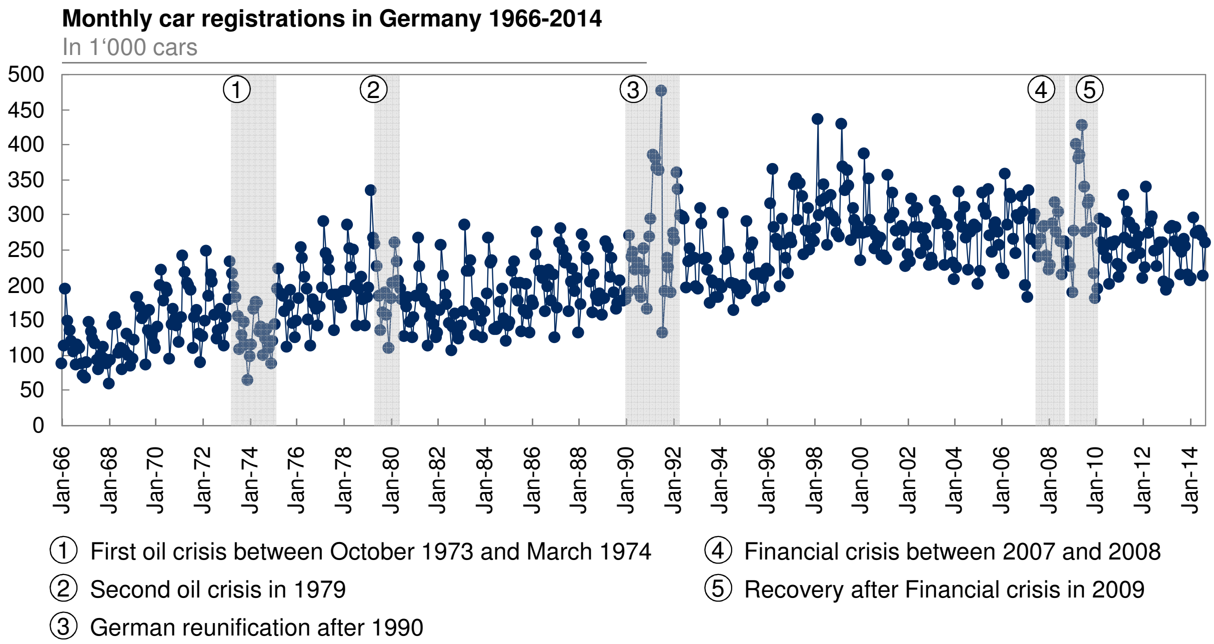

Figure 5.2: Monthly car registrations in Germany between 1966 and 2014 and highlighted macro-economic events (German Federal Statistical Office 2015).

demand patterns is characterized by regular fluctuations into different directions. The idea is to identify those demand fluctuations which are not normal and stressing for the industry and their companies.
An example for demand data is the course of car registrations in Germany between 1950 until 2014. The data is shown in figure 5.2. It can be seen that monthly registrations differ. Demand fluctuations characterized as seasonal trends, as one of the patterns illustrated in figure 5.1, as well as nonlinear courses with turning points can be identified. By highlighting different economic booms and crises within the chart 5.2, it can be seen that these turbulences had an impact on the German car demand. An example of an economic crisis resulting in nonlinear demand decrease is the first oil crisis between 1973 and 1974. Another example for a time period with demand increase is the recovery after the Financial crisis between 2009 and 2010. Both exemplary macro-economic events influenced the German car market resulting in strong demand fluctuations.

The specific time frames, the type of demand fluctuations and their shape are different for every industry. Therefore they have to be identified specifically for every industry. For the car industry, for example, time frames with strong demand fluctuations include:

- Strong demand decreases:
  - Slumps in demand following the oil crisis in Europe between 1973 and 1974,
  - Demand reduction after the Financial crisis in Europe between 2008 and 2009.

- Strong demand growths:
  - Strong increase due to the recovery after the Financial crisis in Germany between 2009 and 2010,
  - Additional demand from Eastern Germany after the German unification.

The selection of the reference time period is the main input for the definition of the stressing demand scenario. Bishop et al. (2007, p. 7) and Ringland (1998, p. 108) explain that the task of identifying and selecting scenario should be done as a group task with representatives from different departments and with different backgrounds. The foresight of developments requires different perspectives which can be achieved by sharing perspectives from different standpoints. Therefore the decision regarding what reference time period and the corresponding demand fluctuation will be selected for the stressing demand scenario should be an entire project team effort. The project sponsors as well as the relevant managers of the production network partners have to be included into the decision. The project team prepares different time period options and presents them to the project sponsors. The final decision requires the support of the project sponsors to ensure the acceptance and buy-in of the project members as well as the included production managers. The course of the demand fluctuations will be the main input to create the stress test demand scenario. Therefore this decision significantly influences the shape of the stressing demand scenario and its generated insights.

Derivation of demand scenarios

With the specific demand fluctuation from the reference time period selected, the demand course has to be transferred to the dimension and magnitude of the focal company. As the demand data for the demand fluctuation can come from historic demand data of the focal company or from public demand data, it has to be ensured that the data is adjusted in its dimension and magnitude to the current requirements of the focal company. The result of this sub-step is a stressing demand scenario used for the stress test of the production network.

In general, two scenario types are available: The first type is called global scenarios and is created for superior areas using highly aggregated data. The second type is a company specific scenario. It is created for individual companies based on their specific influencing factors (Reibnitz 1987, pp. 15–16). This means the level of detail as well as specification of the scenario types differ between the types. For this work the company's specific scenarios are used.

Company specific scenarios are widely used in industry and help to acquire different views on the development of a company. They are usually described as providing "alternative views of the future" (Gausemeier et al. 1998, p. 113). These views are essential as the

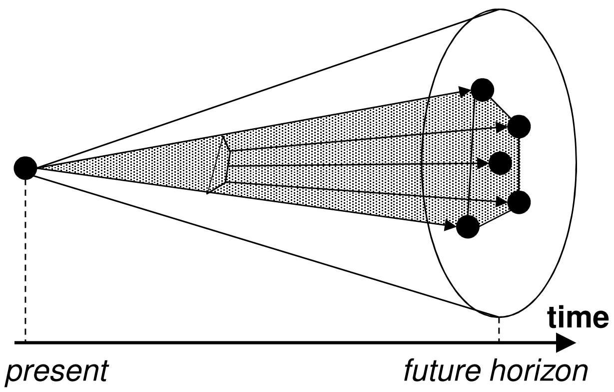

Figure 5.3: Scenarios represent different potential developments of the future, illustration by (Gausemeier et al. 1998, p. 114).

uncertainties and global influences increase and a universally valid projection of future developments is difficult. Gausemeier et al. (1998, p. 114) define a scenario as “a generally intelligible description of a possible situation in the future, based on a complex network of influence-factors”. Figure 5.3 provides an illustration of scenarios. As seen in the illustration, scenarios describe potential future developments from a point of view of the present. For the agility stress test this means that historical demand patterns are used in stressing scenarios to evaluate how the current production network agility is set up to react on it. This prepares the production network for future developments.

As discussed in chapter 3.1.1, Ludwig et al. (2010, p. 65) mentions three scenario types for banking stress tests:

- Historical scenarios,
- Hypothetical scenarios and
- Mont-Carlo-Simulation.

In section 4.1.3 it was explained that the idea of the methodology is to use extreme demand courses to assess the agility of the production network. A further requirement for methodology is to provide results of the agility stress test which achieve a high acceptance at the production management. Therefore the developed methodology relies on the historical scenario as a stress test type. They consist of demand courses derived from historical demand shocks or booms. These courses have been identified based on the identification and analysis of the historical reference time periods. Both demand shocks or booms are a challenge for the production within the production network.
The identified demand course is used as input to create the so called “stressing demand scenarios”. They are characterized as demand courses which consist of strong demand fluctuations for the specific production network.

Transfer of scenarios on production network

The goal of this step of the methodology is to transfer the relative demand fluctuations from the historical demand data to the current dimension of the focal company. The result is one or more stressing demand scenarios specific for the focal company.
This step is required as the demand fluctuations are derived from historical data. Either from historical internal demand data from the focal company in case the product has already a long production history ranging back to the reference time period that is used as a reference. Alternatively, official demand data of comparable products is used as input. The magnitude and dimension of both data sources is different from the demand data that the focal company and its corresponding production network processes today. Therefore the historic stressing demand data has to be analyzed according to its relative fluctuations between specific time intervals. These relative fluctuations can then be used to create the stressing demand scenario for the focal company.
The three-step-process to transfer the demand fluctuations of the selected reference time period is described in figure 5.4. The process steps are:

1. Identification of historic course of demand,
2. Derivation of relative fluctuation between time intervals and
3. Calculation of company specific demand course multiplying relative fluctuations with starting value.

The selected time frame is the basis for the process and the demand scenario that will be the stress test scenario for the production network. In the first step, the time series needs to be analyzed regarding its relative fluctuations between representative and constant time intervals. Time intervals are defined as the duration between two measurements of the time series (Schönsleben 2011, p. 473). The measurements in this case are the demanded products of every time intervals. The size of these intervals depends on the industry and its specific characteristics. For the automotive industry intervals of one month were selected to calculate the relative fluctuations. Within other industries weeks or days can be used. In the example in figure 5.4 one month is adopted.

Within the second step the relative fluctuations between the time intervals during the course of the time series are summarized. They show how strong the demand changed from one time interval to the next is. These relative fluctuations are the input for the third step. To derive the stressing demand scenario, the relative fluctuations of the second step are transferred to the demand dimensions of the focal company. Due to this, a baseline value of the demand dimension of the focal company needs to be defined which is used as a starting value to apply the demand fluctuations. This value needs to be set by the project team. As the goal of the stressing demand scenario is to evaluate how well the production

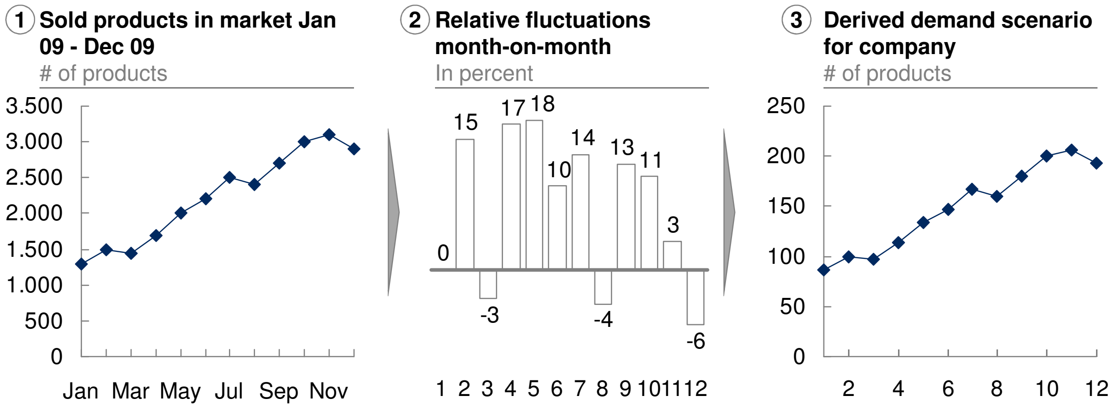

Figure 5.4: Approach to transfer the identified historical scenario to the stressing demand scenario of a focal company (example numbers).

output can be adjusted in order to be fulfilled, the value can be derived from the past production output of the focal company. Good orientation values are, for example, the average production per time interval over a specific time series or the standard utilization of the production capacity. With the starting value defined, the relative fluctuations can be transferred and the relative demand fluctuations of the historical time series can be transferred to create the stressing demand scenario for the focal company. The project team is required to check the created stressing demand scenario according to its reasoning and consistency.
The stressing demand scenario is an important part of the stress test approach. It will be used as a main input for the following steps of the methodology to assess the agility of the production network.

5.2 Modeling and simulation of material flow and profitability

The goal of the second step of the methodology is to create verified and validated models of the material flow in the production network as well as for the economic evaluation of different production network setups. These models are used to simulate the agility of the different production network setups.
In section 5.2.1 an overview over simulation models in general is given. Further the scope of the simulation models for the developed methodology will be defined. In section 5.2.2 the buildup of the material flow and profitability model is explained. Subsequently their combination to the simulation engine is described. The result of this methodological step are validated models of the material flow and profitability of the production network to simulate their agility.

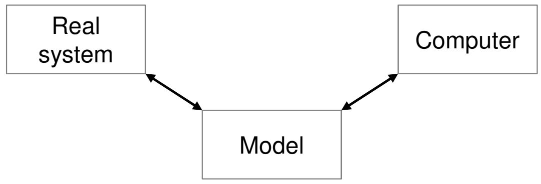

Figure 5.5: A model connects the real system with the computer, illustration by (Zeigler 1976, p. 4).

5.2.1 Overview of models

For the evaluation of the production network agility using a stress test approach, a model of the production network is required. This enables the simulation of different setups of the production network. In the following simulation models in general are introduced. Additionally, the scope and system boundaries of the simulations models for the methodology are defined.

Simulation models in general

The goal of the stress test developed in the outline of this thesis is to understand the agility of a production network. A simulation model of the real production network helps to understand how the production network agility is influenced.
Zeigler (1976, p. 3) separates modeling and simulation: whereas modeling "deals primarily with the relationships between real systems and models; simulation refers primarily to the relationships between computers and models". Figure 5.5 underlines this separation by illustration that a model is a reproduction of a real system.

As defined in section 2.1.2, a production network consists of different companies which provide manufacturing and production services. As these different companies act and interact together toward the accomplishment of some logical end, following Schmidt & Taylor (1970, p. 4) the production network can be seen as a system. Robinson (2003) describes systems such as manufacturing plants, supply chains and transport systems as operating systems (Robinson 2003, p. 3). Wild (2003) defines an operations system as "a configuration of resources combined for the provision of goods or services". With this definition available, a production network can be seen as an operations system as well.
(Robinson 2003) characterizes operations systems by variability, interconnectedness and complexity. A simulation from his point of view helps to predict the system performance. Additionally, alternative system designs can be compared and effects of alternative policies on the system performance can be evaluated (Robinson 2003, pp. 4–7). Law & Kelton (2000, p. 670) emphasize that the greatest overall benefit of using a simulation in a manufacturing environment is that it allows the user to "obtain a system-wide view of the effect

of “local” changes to the manufacturing system”. By doing so, the manufacturing system can be analyzed, demonstrating how changes made to particular machines influence the performance of the overall manufacturing system. Law & Kelton (2000, pp. 3–4) propose to study a system using simulation models for two reasons: firstly to gain “insights into the relationships among various components” or secondly, “to predict performance [of the system] under some new conditions being considered”. Robinson (2003, p. 4) states that “simulation is an experimental approach to modeling, that is, a "what-if" analysis tool. The model user enters a scenario and the model predicts the outcome.”

For the simulation of the production network a computer based dynamic simulation can be used. A dynamic simulation is defined as “an imitation (on a computer) of a system as it progresses through time” (Robinson 2003, p. 2). These computer based dynamic simulations can be applied for different systems, such as operations systems. Bayer et al. (2003) explains that computer based simulation models are well known in the industry, especially in the automotive industry. Campuzano & Mula (2011, p. 3) provide further guidelines about how to use simulation-based modeling.

A simulation model does not attempt to provide an optimum answer (as it is done by, for example linear programming), neither near optimum (as by, for example heuristic models). A simulation model rather predicts the performance of an operations system under a specific set of inputs. It is a decision support system helping the management to make decisions and does not take decisions on behalf of the user, such as done by optimization algorithms (Robinson 2003, pp. 3–4). Simulations help to study the system in focus and gain insights into the relationships among the various components of the systems (Law & Kelton 2000, p. 3).

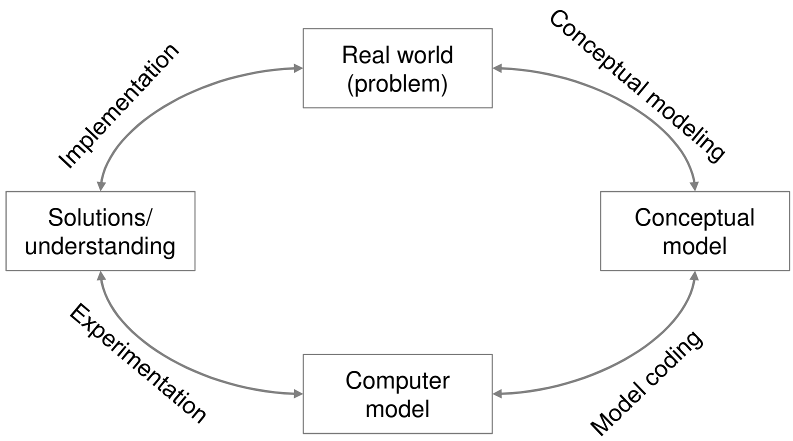

Figure 5.6: Process to build a simulation model (Robinson 2003, pp. 52).

In figure 5.6 Robinson (2003) shows how the real world problem can be translated into a computer model by first creating a conceptual model. There are two results when experimenting with the computer model: First, an understanding of the real world problem is created. This knowledge can be used for the second result, which is to identify solutions for the problem. The solutions can then be implemented.

These reasons and definitions show that a computer based reproduction of the production network in a model can be created. The real world problem of understanding the agility of the production network and improve it, can be investigated using the simulation model. The model can be used to realize simulations of the production network in order to understand its agility performance. Furthermore, the inclusion of the production network simulation in the developed stress test methodology, a characteristic of financial stress tests outlined in chapter 4.1.3 can be fulfilled.
Several steps are necessary to build the simulation models in order to realize practical, realistic and correct simulation models. Banks (1998, p. 16) introduces a process to realize a simulation study. It is illustrated in figure 5.7. This process is used as a structure to create the two models for the material flow and the profitability of the production network.
Whereas the steps “Problem formulation” and “Setting of objectives and overall project plan” were already realized in section 5.1, the steps “Model conceptualization”, “Data collection”, “Model translation” as well as “Verification and Validation” will be explained for every model throughout the following. The step “Production runs and analysis” is part of section 5.3 and the process step “Documentation, reporting and implementation” will be discussed in section 5.4.

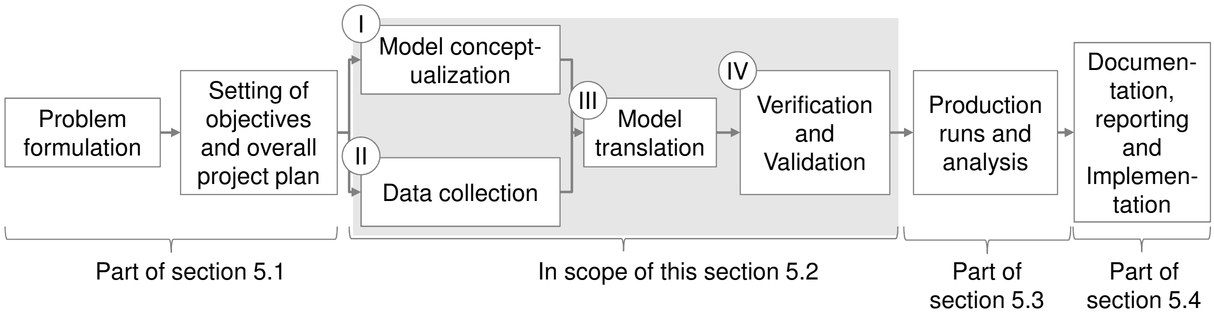

Figure 5.7: Steps in a simulation study, adapted from (Banks 1998, p. 16).

Robinson (2003) mentions three options that are available for developing computer models of real systems:

- Spreadsheets,
- Programming languages and
- Specialist software.

Spreadsheets have a limited modeling flexibility and are rather simple and quickly built within a model. The effort to create models using programming languages is high, as are the time consumption and the application range. Specialist simulation software is often visually interactive. It provides a solution wherein the model can be built quickly for a relatively wide range of applications. Further, it can be validated quickly. This specialist

simulation software is often available for very specific application purposes, such as supply chain modeling, production scheduling or call centers (Robinson 2003, pp. 39–42).
For the material flow of the developed methodology, the two options programming language and specialist software are feasible. The specialist software has already pre-defined components, methods and specific tools for the usage in a production environment available. This simplifies a practical creation of the material flow model. Especially in the area of logistic, material flow and production simulation various specialist software is available on the market. They fulfill a broad range of simulation requirements for production and production networks (Eley 2012, pp. 10–11). Therefore the material flow simulation will be realized using a specialist software.

Scope of models

As explained in section 4.2 the production network in scope consists of different network partners and is lead by a focal company. The network partners include internal production sites of the focal company as well as external suppliers.
To reduce the complexity of the simulation models and to limit the data collection effort a delimitation of the production network replicated in the models needs to be done. At the same time a sufficient expressiveness and credibility of the results has to be ensured. Law & Kelton (2000, p. 265) underline that a delimitation and strict boundary settings of the system in scope are required to ensure reasonable efforts to build up the simulation models.
In Law & Kelton (2000, pp. 267–269) provide a list of guidelines which should be taken into account when determining the detail level of a simulation model:

- Carefully define the specific issues to be investigated by the model and the measures of performance that will be used for evaluation
- Use subject-matter experts and sensitivity analyzes to help determine the level of model detail
- Start with a “moderately detailed” model, which can later be embellished if needed
- Not more detail in the model than is necessary to address the issues of interest, subject to the proviso that the model must have enough detail to be credible
- Level of model detail should be consistent with the type of data available

The guidelines show that at the project start it is important to think about the issues that should be simulated and how the resulting impact can be measured. Law & Kelton (2000) recommend defining the performance measures, such as specific KPIs, to have an orientation how to setup the simulation model in the beginning. For the simulation

models of the developed methodology the KPIs are defined. The adjustable capacity, the speed to adjust the capacity and the profitability will be used to evaluate the simulation model performance.
Guidelines regarding the use of subject-matter experts, starting with a "moderately detailed" model are part of the process introduced in figure 5.7.

5.2.2 Buildup of models

The goal of this step is to create the models to evaluate the agility of different production network setups. This should be done by evaluating the three agility characteristics "amount of adjustable capacity", "speed to adjust this capacity" and "profitability".
The agility characteristics "amount of adjustable capacity" and "speed to adjust this capacity" require an understanding of the capacity development of the production network. "Profitability" focuses on an economical evaluation of the production network. As these perspectives are different it is required to used two simulation models: the first one is called "material flow simulation". It is built up to simulate the output of the production network setups over time. An understanding is gained regarding how different operational measures to increase agility interact with each other. Therefore, insights about the agility characteristics are derived regarding "amount of adjustable capacity" and "speed to adjust this capacity". The second model is named "profitability simulation" and focuses on the evaluation of the profitability of different production network setups. It models the costs and revenues of every production network setup which are used to calculate the profitability.
Both simulation models are combined to a simulation engine. Figure 5.8 illustrates their connection. By using the simulation engine it can be ensured that the agility of the production network can be evaluated holistically along the three characteristics identified in chapter 4.1.1.

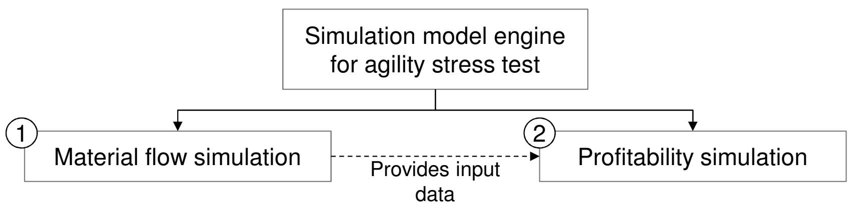

Figure 5.8: Parts of the simulation engine for the agility stress tests.

The material flow model focuses on the simulation of the production processes in the production network and their corresponding information flow. The profitability models on the other hand evaluates the impact of profitability on each production network setup. Figure 5.9 details the data flow between the models. It is important to emphasize that the two parts of the simulation engine needs to be run one after another, starting with

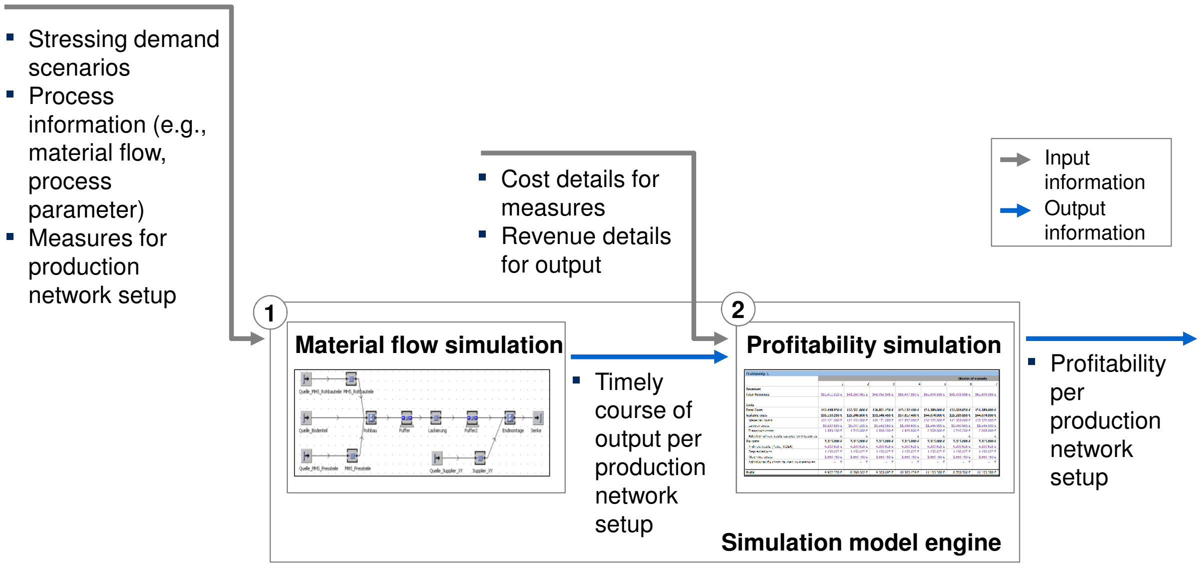

Figure 5.9: Input and output information for simulation engine which consists of the material flow simulation and profitability simulation models.

the material flow model.
The input for the material flow simulation are the stressing demand scenario, different process parameters about the production and transport processes as well as operational measures to adjust the agility of the production network. The output of the material flow simulation are timely courses of the production volume for the stressing demand scenario and for every production network setup. These courses of production volume are directly input information for the profitability simulation. Further input information for the profitability model include cost details for the operational measures such as required investments, fix and variable cost and one-time activation costs as well as revenue details. The output of the profitability model are timely courses of the profitability per production network setup during the duration of a simulation period.

Material flow model

In this model the material flow through the production network is simulated. In the following the process is explained how this model is built up.
Müller-Sommer & Strassburger (2009, pp. 356–359) provide a categorization of logistic simulations which are especially used in the automotive industry. They identify four simulation types which are illustrated in figure 5.10:

- Production site simulation,
- Delivery simulation,
- Supply chain simulation and

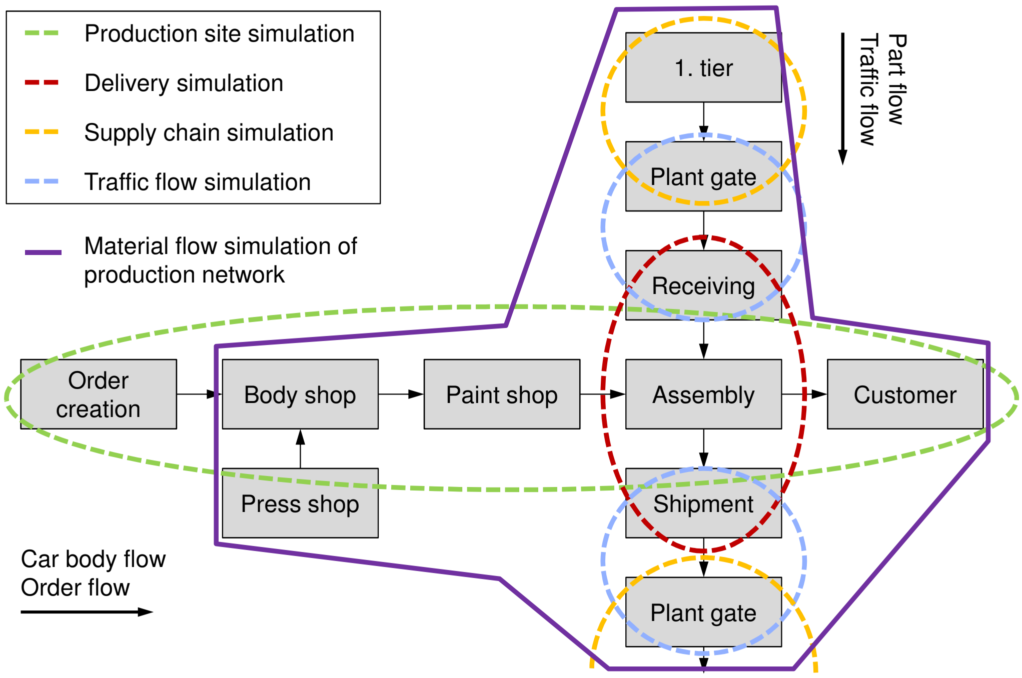

Figure 5.10: Types of logistic simulation models along the car production value stream, adapted from Müller-Sommer & Strassburger (2009, p. 356).

- Traffic flow simulation.

They are separated by characteristics such as system boundaries, level of detail, steps of the production process of a car and the simulated phase during the product design process. Production site simulation and delivery simulation focus on process steps inside a production site. Production site simulation uses a high abstraction level. Müller-Sommer & Strassburger (2009) characterize it as a simulation of capacities which are rigidly connected with each other. The individual production steps are represented as black boxes. It answers questions about the throughput of the process, the inter-connectedness of different work time models or the optimal utilization of the production steps. Delivery simulation has a higher level of detail. It simulates only the process steps receiving, provision and shipment of goods.
Supply chain and traffic flow simulation represent the material flow as well as the means of transportation. Supply chain simulation reflects the delivery chain between the suppliers and the production sites. It answers questions regarding overarching process optimization or the delivery reliability of suppliers. Traffic flow simulation reproduces the usage of the means of transportation inside a production site (Müller-Sommer & Strassburger 2009, p. 356).

The objective of the material flow model is to simulate the material flow in the production network. Therefore it is positioned in the middle of the production site and the supply chain simulation introduced by Müller-Sommer & Strassburger (2009). The production

steps at the production network partners are included into the simulation as well as the delivery chain between the partners. This includes information such as transport times and delivery frequencies. To limit the level of detail of the material flow simulation, the production steps at the network partners are integrated as black boxes.
The material flow model contains the most relevant partners of the production network with their production steps. The selection of the partners should be performed based on the type of parts they supply to the final assembly at the focal company. Methodologies to select the parts and correspondingly their suppliers are:

- ABC-analysis of the parts (or family of parts) to prioritize the parts according to their value,
- Categorization of parts into their delivery agreement such as Just in Sequence (JIS) and JIT- parts or frequently delivered parts and
- Risk evaluation of the suppliers regarding their potential agility limitations.

The model simulates the different production network partners by using a capacity view. Capacity is defined by the quantity which can be produced during a period of time (Schönsleben 2011, p. 28). This means that the simulated elements, for example the production steps at the network partners, are analyzed and transferred to the model by applying a capacity oriented view.
To simulate the various inter-dependencies of the production network setups over the course of time, the DES approach is used. The DES-approach is defined as "representing only the points in time at which the state of the system changes. In other words the system is modeled as a series of events, or instants in time when a state-change occurs" (Robinson 2003, p. 15). Law & Kelton (2000, p. 6) explain further that "in more mathematical terms, we might say that the system can change at only a countable number of points in time". At these points in time different events occur. This approach is opposed to continuous simulation or Monte Carlo simulations. Continuous simulations model a system over time "by a representation in which the state variables change continuously with respect to time" using differential equations (Law & Kelton 2000, p. 87). Cassandras & Lafortune (1999, pp. 53–54) categorize DES as part of system theory and characterize it as a dynamic and stochastic simulation approach.
Further, the DES is a tool to be used in an overall effort to achieve the "digital factory" (Bracht et al. 2009, pp. 121–122). Digital factory is defined as an overarching concept for an holistic network of digital models, methods and tools. These include simulation and three-dimensional visualizations and are integrated through a continual data management (Bracht et al. 2009, p. 11). The Digital Factory effort has several goals: the achievement of a more rapid product introduction on markets, the improvement of product quality, the reduction of production costs as well as an improvement of the production site by creating a digital model of a factory and its environment and to use model simulation

extensively. This effort spans along the whole life-cycle of a product, from the design phase until serial production (Bracht et al. 2009, pp. 51–63).
The simulation software "Tecnomatix Plant Simulation" from SIEMENS was selected for the computer simulation of the material flow model. The software is widely used within the industry, specifically in the automotive industry (Eley 2012, p. viii). It represents a good compromise between a broad range of applications and the implementation support of the simulation model (Eley 2012, p. 11). Nonetheless, other simulation software can be used to simulate the material flow within the production network.
Within the following the process is explained of how the material flow model is created. The process is structured along the approach to create a simulation study outlined in figure 5.7.

I. Creating a conceptual model of the production network The build up of the material flow simulation model starts with the creation of a conceptual model of the material flow of the production network. Bangsow (2011, pp. 1–8) underlines that good preparation of a simulation model is required to fulfill a successful simulation of complex production systems.
The creation of the conceptual model starts with the creation of a value stream of the production network. The conceptual needs to be aligned with the level of detail needed. Process-mapping techniques such as the Value Stream Mapping method can be used. A value stream can be defined as "all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product" (Rother & Shook 2009, p. 6). In the case of the production network in scope, it means the actions from the tier-1 suppliers to the focal company are taken into consideration. Rother & Shook (2009, p. 7) describe Value Stream Mapping as a "tool that helps you understand the flow of material and information as a product makes its way through the value stream". Value stream mapping is a top-down approach which means that "the system is viewed as a whole, and important potential improvements are identified in an early phase" (Abele 2008, p. 316).
Value Stream Mapping has the advantage of providing the freedom to set the level of detail as it is needed (Rother & Shook 2009, p. 23). For the production network in focus the detail level can be set at connecting the process steps of the network partners by summarizing them in process boxes. A detailed description of the operational processes is not included. Another advantage of the methodology is its fame and acceptance within the industry. This simplifies the application. Additionally, it facilitates the discussion among the production network partners as it provides a transparent overview of the material and information flow in the production network in scope. Various publications provide detailed descriptions of how the Value Stream Mapping method can be used, for example Erlach (2007), Rother & Shook (2009), Roessler et al. (2014) and Albrecht (2014) with an extended Value Stream Method incorporating potential changes in a factory.

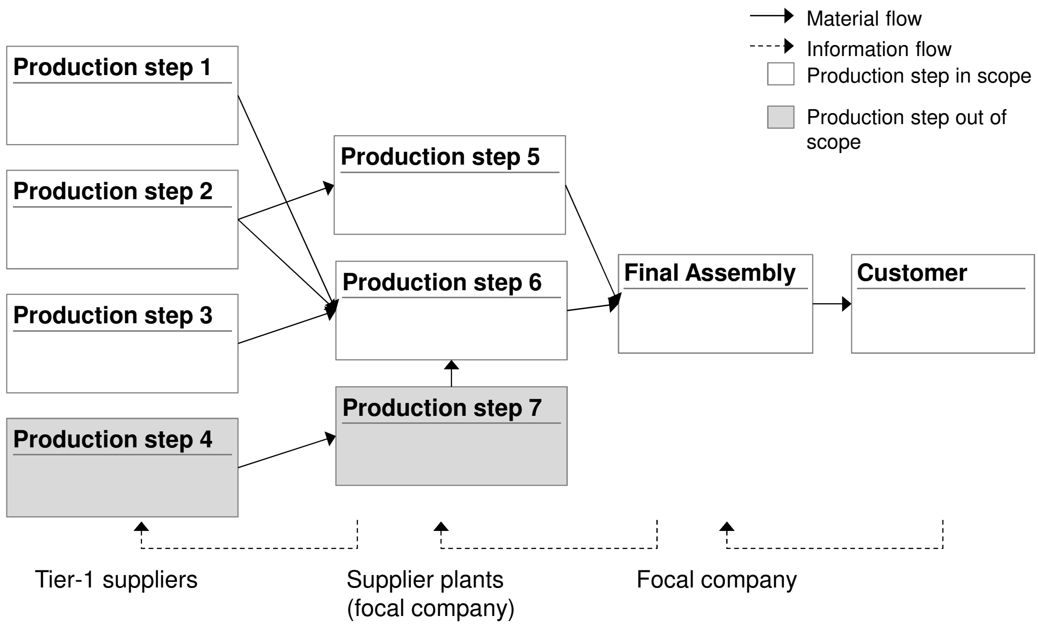

Figure 5.11: Generic conceptual model of the production network, illustrating which production steps will be part of the model.

The conceptual model of the material flow provides a holistic overview over the production network in scope. The main process steps of the network partners and transport steps connecting them are included. Detailed process data is not included yet. Figure 5.11 illustrates the idea of the conceptual model. It is important to include all of the relevant steps of the production network in scope. This effort requires the discussion with all relevant network partners which are part of the agility stress test.
The process boxes illustrated in figure 5.11 represent production steps of the production network in focus. The illustrated production steps will be simulated in the material flow model. In the process boxes the process data of each step is collected and illustrated.

II. Data collection After having created a conceptual model of the production network, it is used as a framework to collect detailed process data. This is done for every partner as well as the production steps of the production network. Figure 5.12 provides an overview of data typically collected for every step in the production network. The collected data is used to calculate the production capacity for every production step in scope.
For the realization of the data collection, formats such as interviews, data collection workshops with different stakeholders of the production network as well as data analyzes from computer systems, for example the ERP- or MRP-system, are used. The conceptual model is used to collect and aggregate the collected process data.
The following functions of the production network partners should be contacted for the data collection:

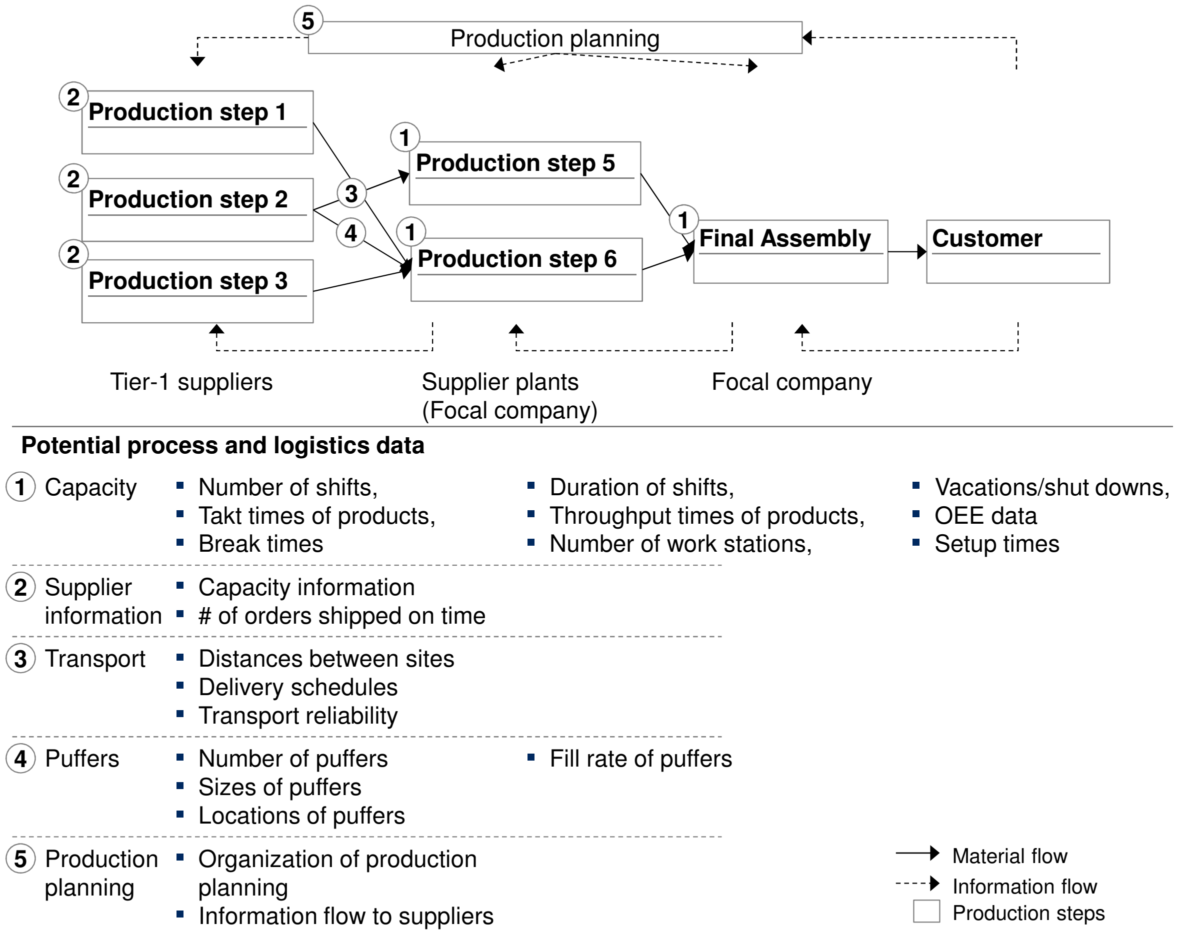

Figure 5.12: List with typical process and logistics data to be collected from production network partners to create the conceptual model of the production network in scope.

- Production planning department
- Sourcing department
- Supply Chain department
- Sales department

The process boxes of the conceptual model are thereafter enriched with the collected process data. The result of this data collection step is a conceptual production network model enriched with the required process data of each production step. This resulting process model of the production network can be used for different purposes: It can be used as a tool for the communication with the involved network partners and managers. Another option could be the usage as a pure data collection tool as input for the simulation model. Furthermore it can be used to review with production management. This is a first step to create acceptance at the management of the computer model which will be created afterwards. Law & Kelton (2000, pp. 269–282) recommend using such tools to

ensure buy-in and acceptance of the created models by management.
It is useful to run a final workshop with the main representatives of the functions and network partners involved to discuss the end version of the conceptual model which is enriched with collected process data. The goal is to verify the process and information flow as well as the collected data of every process step with the parties involved. This is an important first step for the overall acceptance of the computer model and its results. With this conceptual model still on paper, it can be transferred in the next step into a computer model of the production network in focus.

III. Translation to the computer model As mentioned above, the simulation software Plant Simulation is a widely used DES-software tool in the industry. It offers a wide range of material flow objects that can be used to simulate the production and transport flow between the network partners.
In Plant Simulation, hierarchical simulations can be created. This means that if one network gets too complex for the simulation, it can be divided into smaller ones. Those smaller networks can then be combined to overarching networks (Bangsow 2011, p. 313). In the case of the production network in focus, the material flow of the different production network partners are simulated in specific networks in Plant Simulation. These networks are then integrated into the production network in scope.
The objects in Plant Simulation are organized in a class library that can be separated into frames, motion units and material flow objects. Figure 5.13 shows a screenshot of the Plant Simulation software with its illustrated class libraries. The frame is the basis of the simulation model and all material and information flow as well as resource objects are integrated within it. This allows for creating the hierarchy of different frames (networks), representing different production network partners.

Different material flow objects are available that represent elements of the simulation model. They contain specific, pre-defined functions enabling to model the production quickly by re-arranging them to the requirements of the simulation. Often the pre-defined functions of the objects have to be adjusted to achieve a sufficient picture of the production reality (Bangsow 2011, p. 57).
The motion units represent the material flow in the model. They can be orders or physical objects such as transport boxes or vehicles. These objects are moved and handled throughout the model.
The material flow objects contain objects to simulate machines, storages and material flow technologies (Eley 2012, pp. 35–36). The material flow objects can be separated into movable and unmovable material flow elements. Movable elements represent physical parts which are moved through the model, for example vehicles or transported material. Unmovable elements actively hold the movable elements in the system, for instances conveyor systems or assembly stations, (Bangsow 2011, p. 57). Albrecht (2014, p. 110) provides

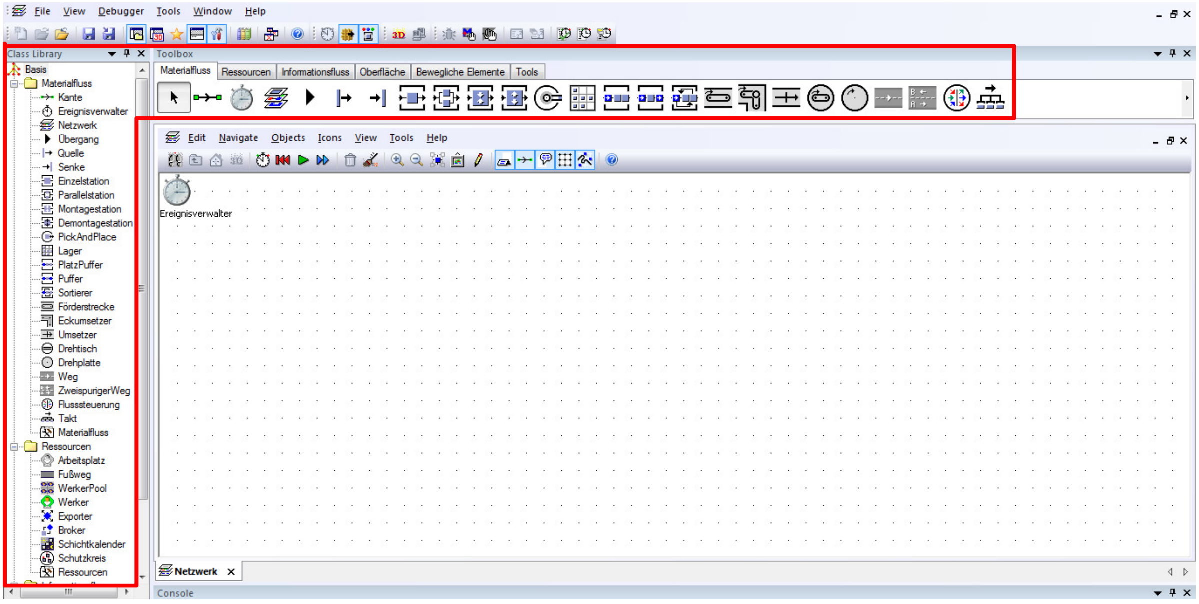

Figure 5.13: Screenshot of the software Plant Simulation with the class libraries highlighted.

an overview over the material flow objects in Plant Simulation with specific examples. Further, objects such as data structures and resources are available in Plant Simulation (Eley 2012, p. 36).

By using these objects in Plant Simulation, the conceptual model created in the beginning of this section can be transferred to the computer model. By doing so, the predefined attributes of the material flow models, for example the processing and change over times, disturbances or adjustments of the shift calendar for different machines can be adjusted to the requirements of the real system. It is also possible to use stochastic distributions for attributes to ensure a realistic simulation of the reality. An example would be to simulate the day-on-day variation of the throughput of the production network by using stochastic values for breakdowns, changeovers or other interruptions of the specific material flow elements.

If the provided functionality of the standard objects is not sufficient to create realistic system models or if the simulation model should be influenced during a simulation run, which in practice is very often the case, Plant Simulation provides an own programming language (Bangsow 2011, p. 9). The language is called "SimTalk". SimTalk enables the user to create functions and procedures to control and influence the simulation model as needed (Eley 2012, p. 47).

With the functionality of Plant Simulation at hand, the conceptual model of the production network can be replicated as a computer based simulation model in Plant Simulation.

IV. Verification and validation of the simulation model After having built up the model in the simulation software, the model needs to be verified and validated. These two steps are shown as step four in figure 5.7. Their overall goal is to avoid incorrect conclusions from the simulation model which leads to wrong decisions. This is why verification and validation should always be part of every simulation study (Rabe 2008, p. 47). Law & Kelton (2000, p. 265) emphasize that a “valid” simulation model can be used to make decisions about the simulated system similar to those that would be made by testing it directly with the system.

Verification and validation of the model are closely connected to each other. Figure 5.14 shows their timing and relationship to establish credibility with the simulation model stakeholders. Verification deals with “determining whether the conceptual simulation model (model assumptions) has been correctly translated into a computer ’program’, i.e. debugging the simulation computer program”. Validation means “the process of determining whether a simulation model (as opposed to the computer program) is an accurate representation of the [real] system, for the particular objectives of the study” (Law & Kelton 2000, pp. 264–265). Banks (1998, p. 17) points out that the verification of the simulation model should be done as a continuing process and should be supported by the usage of interactive run controller, or debugger. Figure 5.14 supports this statement by showing that verifying and validating the model during the model creation process leads to “correct” results. These correct results then create credibility at the stakeholders of the simulation model. This can be essential for the management of the different production network partners. A helpful approach is to interact with the employees involved in the agility evaluation effort as often as possible to show the simulation model itself, or parts of it, and the results obtained with it. This helps to test different points: First, if the model still answers the right problem as the problems get clearer during the process, second to check if the (first) results are correct and make sense and to maintain the interest and involvement in the study which finally leads to a higher understanding and acceptance of the simulation model and its results (Law & Kelton 2000, pp. 275–276). The network character of the material flow model requires special efforts to ensure a broad involvement all the relevant stakeholders. Their number is high and divers as they include people from different internal departments, from potentially different internal sites as well as from external partners. Nevertheless regular interaction with the partners about the progress of the model and its results, improves the validation and verification of the model and ultimately its credibility at the involved partners.

Balci (1998, pp. 345–354) provides a list of more than 75 techniques for verification, validation and testing of simulation models. These techniques differ in complexity and realization effort and can be divided into quantitative and qualitative techniques. The application of the techniques depends on the knowledge of the user as well as potential effort that can be spent on validating and verifying the simulation model. All of these techniques aim to ensure that the model itself is an accurate representation of the actual system being studied, meaning, the validity of the model. This matching can be measured by the extent of agreement between data of the real system and the model-generated data

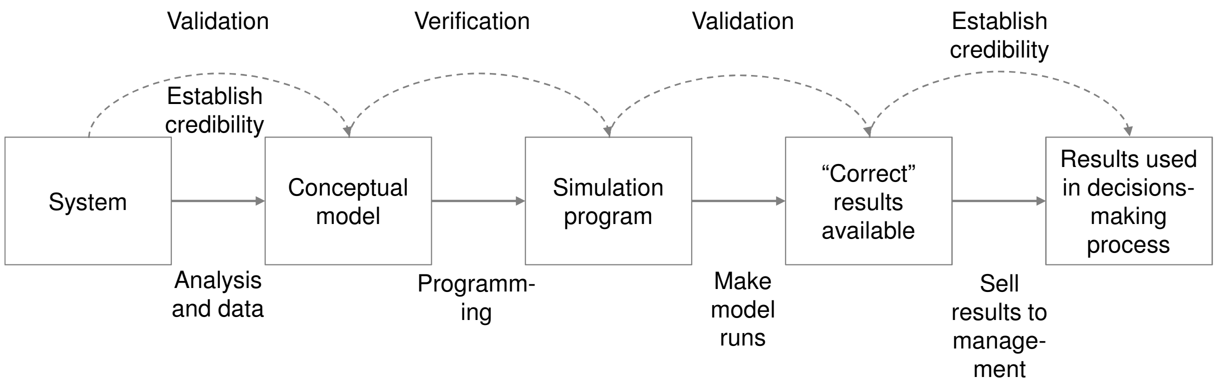

Figure 5.14: Timing and relationship of validation verification and establishing credibility (Law & Kelton 2000, p. 266).

(Zeigler 1976, p. 5). Nevertheless a simulation model remains an approximation to the actual system and it is not possible to create absolute model validity, no matter how much effort (and hence money) is spent (Law & Kelton 2000, p. 265). The mentioned techniques can be used to check how close the outcome of the simulation model gets to the outcome of the real system. Further techniques to improve the verification process as well as the validity and credibility of the model are provided in (Law & Kelton 2000, pp. 269–282).

Banks (1998, p. 17) mentions that an ideal way to validate a model is to compare its model output to the output of the real system, providing the information is available.

In the case of the material flow simulation, historical data is usually available in the form of output data of the production network over several periods of time, for example months or years. The production data of the production network leader combined with the call-off data of the production can be used to validate the simulation model of the production network. The comparison of this data with the model output appears to be practical.

Eley (2012, p. 16) lists further qualitative techniques to validate simulation models. Besides the comparison of the model output with real data, the techniques 'structured model review' and 'sensitivity test' are mentioned as applicable in practice and to be a good compromise between achieving a good grade of model accuracy and requiring a reasonable realization effort.

The result of this step of the methodology is a validated material flow simulation model of the production network in scope. The model is able to simulate the major production steps of the network leader as well as at the involved network partners. Further the transport relations between the partners can be simulated in the model.

Profitability model

With the created material flow model on hand, the profitability model as the second part of the simulation engine, as shown in figure 5.9, can be created.
The profitability represents the third characteristic of agility, as explained in section 4.1.1. The profitability is calculated for the focal company. It takes all the generated revenues and costs during the stressing demand scenario into consideration. Profitability evaluation of the production network setups aims to estimate the financial situation of every production network setup. This means the objective is not limited to the evaluation of the costs of the potential measures, but to additionally assess the potential revenue which can be generated with the production network setup. With this information available, the profitability of every production network setup can be estimated. To evaluate the profitability of every production network setup, its EBIT will be calculated. In the following the process to create the profitability model will be explained.
To create the profitability model, the same steps as for the creation of the material flow model outlined in figure 5.7 are required. As for the material flow model, the steps "Problem formulation" and "Setting of objectives and overall project plan" were already done in section 5.1. In the following the steps "Model conceptualization", "Data collection", "Model translation" as well as "Verification and Validation" will be for the creation of the profitability model.

I. Creating a conceptual profitability model The challenge for building the profitability model is to gain understanding of the profitability development of the production network over time. The concept of overcoming this challenge is to use the EBIT as a measure to structure the profitability evaluation of the production network. Another possibility would be the usage of the net income of the production company during a period as a profitability measure. The calculation of this measure would be more complex as it requires to integrate interest expenses as well as taxes. These values are financial information which do not help to gain more insights into the profitability of a firm's operations. As this is however the objective of the profitability evaluation, the EBIT calculation will be used as a profitability measure. To realize this approach, the following simplifications are required:

- Earnings are generated by selling the produced products; other revenue streams such as financing, cross-selling etc. are not included in the EBIT-calculation.
- Every product which is produced according to the demand scenario is also sold on the market.
- Possible investments required to fulfill specific measures are only outlined. A cash-flow analysis is not done.

- Distribution ratio for indirect costs need to be created in a pragmatic way.
- Research and development costs are not included.

EBIT is an important measure of the income statement of a company and is defined as "a measure of the profitability of the firm's operations abstracting from any interest burden attributable to debt financing" (Bodie et al. 2013, p. 447). This means that EBIT represents the earnings generated by a company's operations and excludes financing costs. This simplification is reasonable for the purpose of the profitability evaluation model.

Operating revenues
Net sales
- Operating expenses
Costs of goods sold
Selling, general, & administrative expenses
Other
Depreciation
= Earnings before interest and incomes taxes (EBIT)

Figure 5.15: Break down of EBIT elements, adapted from (Bodie et al. 2013, p. 447).

Figure 5.15 illustrates the elements of the EBIT. The first part are operating revenues derived from the net sales of a company. Then all the operating expenses are subtracted. Following Bodie et al. (2013) these operating expenses can be divided into four categories:

- Cost of Goods Sold (COGS), which are the direct costs attributable to producing the product sold by the firm,
- Selling, General and Administrative Expenses (SG and A) which correspond to overhead expenses, salaries, advertising,
- Other costs which are costs of a firm that are not directly attributable to the production and are primarily nonrecurring, as well as
- The depreciation of relevant machines and buildings.

The difference between the generated revenues by the company and the operating expenses is called the operating income. To obtain the EBIT, the income (or expenses) from other sources, primarily nonrecurring, has to be added (Bodie et al. 2013, p. 447).
The operating revenue can be calculated based on the quantity of products which are produced over the course of the scenario. These numbers are obtained from the material flow model and are an important input for the profitability model. The produced quantity is multiplied by the corresponding net sales price of each product. This sales price can vary over the course of the scenario. If required, this change needs to be represented in the profitability model.
On the other side, all costs which occur during the production of the products need to

be included. These costs can be broken down as mentioned above. Figure 5.17 provides an overview of different costs. The biggest part of the costs are the COGS. Following Schroeder et al. (2009, pp. 196–198) the COGS of a company during one period include expenses such as:

- Materials,
- Labor and
- Change in inventory.

The SG and A can be split into two categories: Whereas selling expenses focus on costs that are directly related to sales, for example advertising or salesmen salaries, the SG and A include all overhead and administrative costs that are required to run a company (Bernstein 1974, pp. 529–534). Other costs "should normally be rather immaterial in relation to other costs" (Bernstein 1974, p. 535). Depreciation are the costs for long-live assets such as properties, plants and equipment. These costs are allocated over their useful lives. The considered depreciation amount of a period depends on the depreciation method that is used which is determined by the finance department (Bernstein 1974, pp. 226-232).
Bernstein (1974, pp. 224–226) explains that costs can be separated into variable and fix costs. Whereas variable costs can "vary in direct proportion to activity", fix costs "remain relatively constant over a considerable range of activity" (Bernstein 1974, p. 225). They additionally state that costs can be classified into different areas depending on the purpose, such as direct product costs or joint product costs (Bernstein 1974, pp. 224–226).
In the outline of this work the costs for the EBIT calculation will focus on the COGS. The reason for this is that this cost category can be directly influenced by the operations of the focal company and its production network. The COGS will be broken down into variable and fixed parts of the costs which can be assigned to one product.
Figure 5.16 shows an example structure for the EBIT calculation of a focal company producing cars. It can be seen that the elements operating revenues and operating expenses are influenced by specific drivers. The Operating revenues depend on the produced cars during a specific time period and their selling price. The operating expenses are divided into the cost elements COGS, SG and A, Depreciation and Others. For each of these cost elements specific drivers could be identified.

The result of this step is a conceptual model to calculate the EBIT of the product in focus with its corresponding production network. It is important to point out that the conceptual model needs to be adjusted to every specific production network leading company.

II. Data collection After conceptualizing the model as exemplary shown in figure 5.16, a profound data collection needs to be done. To be able to create a profitability model in order to calculate the EBIT of the production of a product, the data outlined in table 5.17

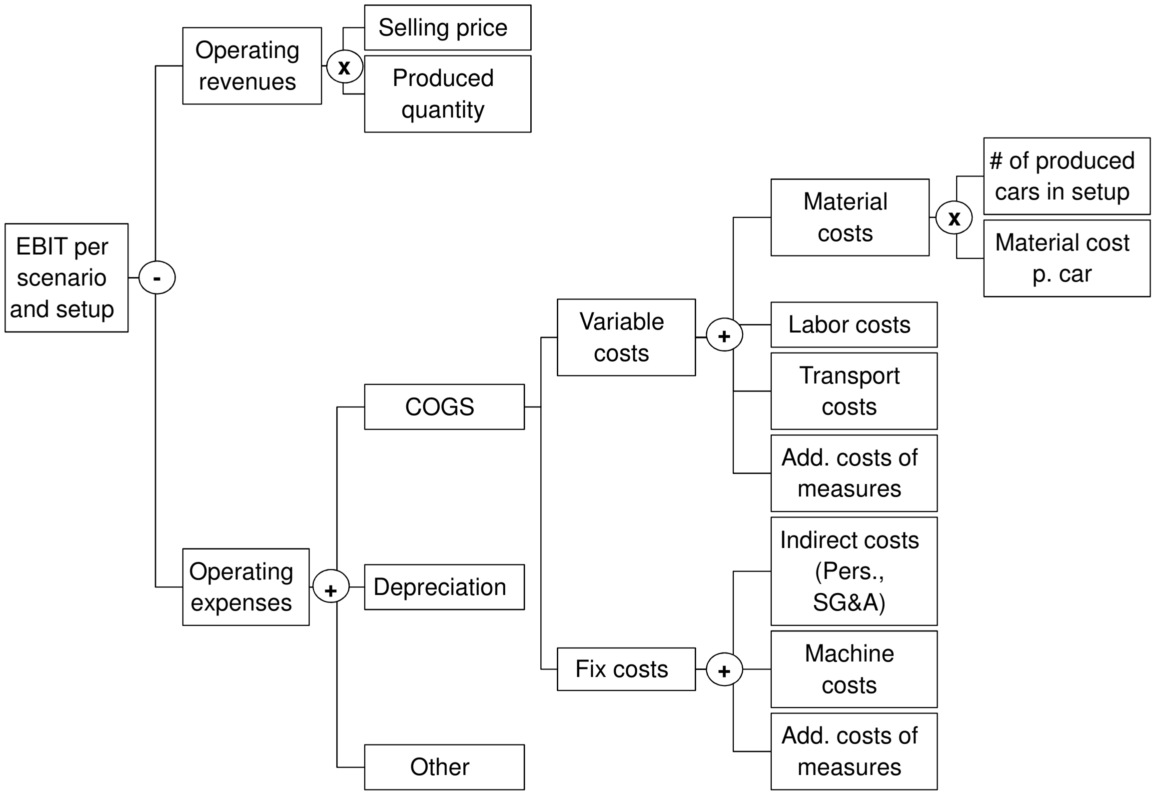

Figure 5.16: Example of the EBIT break down into the main components, derived from (Bernstein 1974, p. 477).

needs to be collected. Interviews need to be conducted with employees of the accounting and controlling department to collect the required data. It is helpful to create a list with the data required and ask the representatives of these departments to complete it.

III. Model translation To create a computer model which simulates the profitability development, a spreadsheet model is used. The software Microsoft Excel is a common tool which offers diverse functions to model the revenue and cost structure of every production network setup for the profitability model.

It is recommended to use a rigid structure to build up the model in Excel and to consequently use different spreadsheets modeling all the EBIT elements. Depending on the size of the production network in scope, different data sources need to be integrated and processed. Literature on how to build up financial models using spreadsheet software, especially in Microsoft Excel, can be found for example at Sengupta (2004) and Jackson & Staunton (2001) who provide tips and examples to build good financial models in Excel. The results of the model are outlined in figure 5.18.

IV. Model verification and validation After the translation of the model to the Microsoft Excel software, the validation and verification of the profitability model need to be

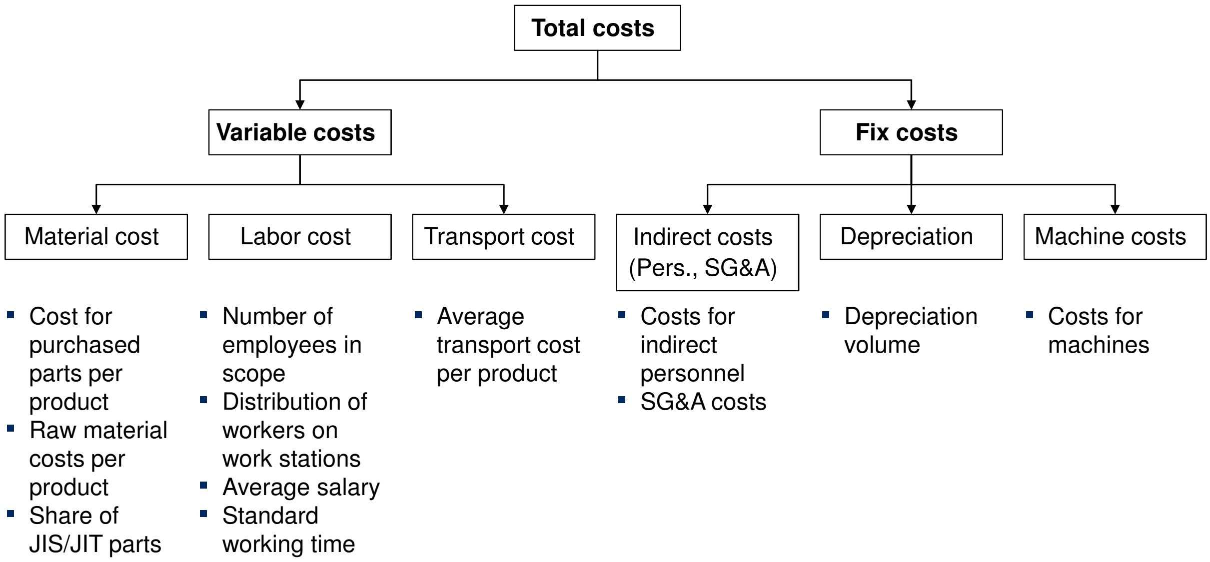

Figure 5.17: Data needed for the profitability model.

EBIT, €					
	Time periods				
	1	2	3	4	5
Operating revenues					
Net Sales	99.351.233 €	92.082.146 €	96.713.683 €	101.324.121 €	105.924.008 €
Operating expenses					
Total Costs	**89.979.160 €**	**83.964.190 €**	**87.796.660 €**	**91.611.670 €**	**95.417.950 €**
Variable costs	**82.210.410 €**	**76.195.440 €**	**80.027.910 €**	**83.842.920 €**	**87.649.200 €**
Material costs	73.452.600 €	68.078.400 €	71.502.600 €	74.911.200 €	78.312.000 €
Labour costs	7.345.260 €	6.807.840 €	7.150.260 €	7.491.120 €	7.831.200 €
Transport costs	1.412.550 €	1.309.200 €	1.375.050 €	1.440.600 €	1.506.000 €
Additional var. costs caused by measures	- €	- €	- €	- €	- €
Fix costs	**7.768.750 €**	**7.768.750 €**	**7.768.750 €**	**7.768.750 €**	**7.768.750 €**
SG&A	5.018.750 €	5.018.750 €	5.018.750 €	5.018.750 €	5.018.750 €
Depreciations	1.306.250 €	1.306.250 €	1.306.250 €	1.306.250 €	1.306.250 €
Machine costs	1.443.750 €	1.443.750 €	1.443.750 €	1.443.750 €	1.443.750 €
Additional fix costs caused by measures	- €	- €	- €	- €	- €
EBIT	9.372.073 €	8.117.956 €	8.917.023 €	9.712.451 €	10.506.058 €

Figure 5.18: The parts of the profitability model of a fictitious production network example in overview.

done as for the material flow model. It is important to re-emphasize that the validation of the model should always be done while building up a model. Approaches for model validation were explained in detail in section 5.2.2 and are shown in figure 5.14.
The verification of the model is recommended to be done with representatives of the accounting and controlling department as well as from the production department. This cross-department exchange and discussion is helpful to deepen insights about the model. The mixture of the financial and operational view helps to trigger discussions about the model leading to a further improvement.
With the validation and verification of the profitability model finished, the second part of the simulation engine as described in figure 5.8 is completed.

5.3 Agility evaluation of production network setups

The objective of this third methodological step is the agility evaluation of different production network setups. This is done by systematically running the simulation engine introduced in section 5.2.
In the course of the first sub-step production network setups are created. They consist of different operational agility measures and represent different agility levels. In section 5.3.2 it is explained how the production network setups are included in the simulation engine and how experiments with the simulation engine are realized. The last step in section 5.3.3 comprises the analysis of the results gained from the experiments.
This leads to an understanding of the inter-dependencies, identification of bottlenecks and "hinderers" of higher agility level in the process flow of the production network. These insights can consequently be used to adjust the operational measures in the production network setups and achieve agility levels that are required by the management of the focal company.
The goal of the simulations, as outlined by (Law & Kelton 2000, p. 3) and (Eley 2012, p. 4), is to study a system, gain insights about it and understand its performance and behavior in detail. To realize this goal, the performance of the system is analyzed by systematically changing input parameters and observing how the performance of the system varies. In literature this approach is described as experimentation with the simulation model. The approach can be described as a "what-if" approach and requires constant experimentation by the user to ensure the required insights are gained and sufficient understanding about the system is obtained. This can be done by continuously adjusting the input parameter of the simulation engine and see how the output of the model evolves (Robinson 2003, pp. 3–4). This process is described as an iterative process and is illustrated in general in figure 5.19. It demonstrates that inputs for the simulation models are used to generated results. Once results are available they can be used to learn and create an understanding about the real system that is replicated in the simulation model.

The generated understanding enables to adjust the inputs of the simulation model more target-oriented towards the required results. This can be done by using "what-if" analyzes. This means that inputs are changed and the directly obtained results are analyzed systematically. By repeating this process the performance of a system can be evaluated.

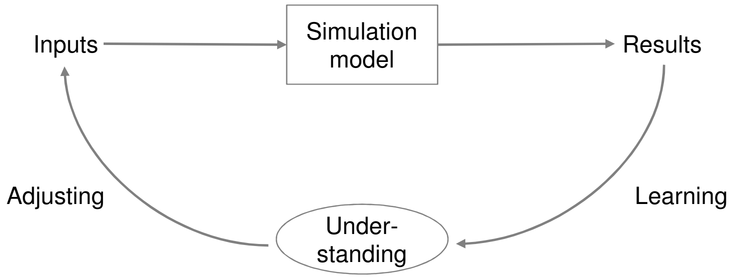

Figure 5.19: Iterative experimentation process during simulation by doing "What-if" analyzes (Robinson 2003, p. 53).

The stressing demand scenario is provided as input from the first methodology step. It is analyzed by the project team of the agility stress test. Operational agility measures are collected on how to react along the production network to the stressing demand. They are combined to a specific agility level and are described with operational information. This is required to integrate them in the simulation engine in the next step. With the different agility measures of one agility level integrated into the simulation engine of the production network, the simulation engine is run. The outcome is analyzed regarding its agility. It is evaluated along the three agility characteristics by using the KPIs. If the expected agility of the production network setup is not sufficient, the operational measures have to be adjusted. Therefore the process is repeated for achieving an increased agility level. Figure 5.20 shows this experimentation process applied for the agility stress test.

In the following the details about the evaluation of the production network agility using the simulation engine will be explained.

5.3.1 Production network setups

The goal of this sub-step of the methodology is to systematically identify production network setups which enable the production network to react to the stressing demand scenario with their agility.
A production network setup is defined as a set of operational measures which have the goal to increase the agility of the production network. These measures are called agility measures. Agility measures are available for the production network partners. The identification and combination of the different agility measures to the production network setups is done by the project team. The team discusses them with involved stakeholders, for example, with the production planning of the focal company and production network

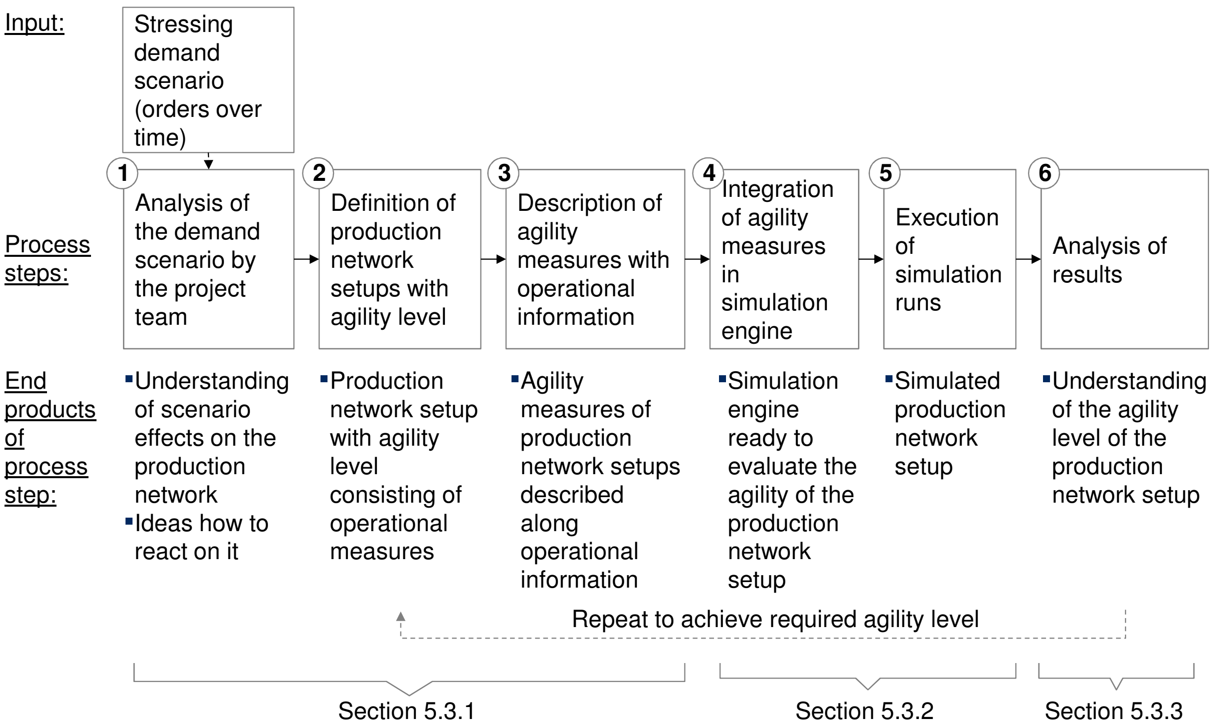

Figure 5.20: Process to systematically evaluate the agility of the production network setups by using the simulation engine.

partners. The nature of specific agility measures differ in their required time of activation and impact. Examples are the usage of overtime accounts by the production network partners, the usage of contractual workers or outsourcing of work content to third parties. The agility of every production network setup is evaluated by running the simulation engine explained in section 5.2. The simulation engine evaluates the inter-dependencies of every individual measure with each other. Thereby the overall agility of the network setup can be evaluated by analyzing the resulting output performance of the production network setups according to the agility characteristics. In summary, it can be said that production network setups are characterized as:

- Set of (operational) measures along the production network that are arranged in different agility levels,
- Created for specific demand scenario,
- Derived by the project team and
- Input for simulation engine

The initial production network setup has no activated agility measures to its disposal to react on the stressing demand scenario. The initial setup is designated as a setup

producing an "average" output from the past, for example, prior months. It can also be seen as the departing point for which the new production network setups with increased agility can be derived. This setup represents the "as is" situation of the production network as it is modeled in the material flow simulation in section 5.2.
The production network setups can be arranged along their agility levels. It is helpful to define expected agility levels of the production network setups at the beginning of the agility evaluation. They should be derived from the goals of the agility evaluation and be aligned with the project sponsors. This helps to structure the idea generation process for the selection and identification of the agility measures. Additionally the identified agility measures can be allocated directly to the different agility levels. Examples of different agility levels could be the creation of "high agility" and "very high agility" production network setups. These levels can be used as a structure to classify the identified measures. The production network setup with the current agility represents a set of agility measures which the focal company can activate in its production and along its affiliated production network. These agility measures are already available and known by the production management of the production network partners derived from their daily work. They can be activated relatively quickly. To identify production network setups which increase the current agility level, the iterative process illustrated in figure 5.20 needs to be conducted. A guiding question leads to a targeted process:

> What measures in terms of labor, assets, operations and supplier management can be taken to increase the agility of the overall production network?

This means which agility measures can be selected to adopting the production network output as close as possible to the course of the demand curve from the stressing demand scenario.
As discussed in chapter 4.2 the production network is organized in a process flow with several inter-connected production steps conducted at the production network partners. Bottlenecks in the process flow limit their throughput and hence the agility of the production network. The identification of the bottleneck is required to define agility measures which release it. With one bottleneck at a process step solved, the next critical process step can turn into the next bottleneck. The systematic consideration of bottlenecks first appeared in the "Theory of Constraints", introduced by Goldratt & Cox (1984), which discusses static bottlenecks. The phenomenon of highly dynamic bottlenecks shifting between different resources is called shifting bottlenecks (Schuh, Potente & Fuchs 2013, p. 214). Different approaches of production controlling concepts are available which try to solve this challenge. For each of the identified bottlenecks specific operational measures need to be identified and implemented. By doing so the bottlenecks can be released and the throughput as well as the agility can be increased.
Generally spoken, potential agility measures can be found within the focal company or within its production network. In the focal company, potential measures can be struc-

	Inside the focal company			Within the production network
Measure category	Operational	Labor	Asset	Supplier
Examples	▪ Overall equipment effectiveness (OEE) improvements ▪ Takt time adjustments ▪ Multi product line	▪ Adjustment of shift numbers ▪ Usage of overtime-accounts ▪ Adjustment of working days	▪ Investments or sale of machinery ▪ Upfront investments in additional buildings ▪ Leasing concepts for machines or buildings	▪ Adjust call-off quantity with suppliers ▪ Adjust delivery frequency ▪ Usage of external partners (e.g., in-/out-sourcing) ▪ Include build-operate-transfer concepts (e.g. pay-on-production)

Figure 5.21: Examples of measures to increase the agility of the focal company and its production network.

tured into labor, process and asset related measures. Additionally, there are supplier related measures for the production network. Figure 5.21 provides a categorization of the potential measures and a list with examples. Further inspiration and ideas for measures to increase the agility can be found for factories in Wagner (2012, pp. 121–133) and Koch (2011, pp. 291–346) and for supply chains in Singer (2012, pp. 238 ff.).

For the identification of the agility measures for the production network setups with increased agility levels, it is recommended to run "idea generation" workshops. Participants should be from departments such as production planning, supply chain management, sourcing and representatives of key suppliers. Additionally it is helpful to include the participation of the top management of the focal company, for example the COO. This ensures the identification of ambitious agility measures to achieve the required agility targets defined at the start of the methodology during the project setup.
Since the stressing demand scenario is challenging in terms of demand fluctuation during a short period of time, the elaboration of appropriate agility measures to increase the production network agility can be challenging for the team involved. Therefore it can be helpful to engage external inspiration for their identification. Visits to known industry leaders of agility, participation at specific conferences, cooperation with universities or with specific industry associations can be helpful. The goal of these efforts is to receive inspirations about agility measures which ambitiously increase the overall agility of the production network.
To ensure that the identified agility measures can be transferred to the simulation engine, operational information describing them is required. Its needs to be collected by the project team. This operational information is structured along the three agility characteristics and include:

- Implementation time of the measure which based on Wagner (2012, p. 49) and

(Heldmann et al. 2015, p. 37) can be separated into

  - Point in time when decision about measure is taken,
  - Ramp-up time until full impact of measure and
  - Start of impact of the measure.

- The maximum run time, if the usage of the measure is time-limited (for example, usage of overtime accounts with maximum and minimum limits),
- The additional costs that occur when the measure is activated:
  1. Sum of variable costs
  2. Sum of fix costs
  3. One-time activation costs
  4. Additional costs per unit
  5. Required (upfront) investments.

To enable a comprehensive evaluation of the agility measures additional information are required such as:

- Depreciation time applied in the company,
- Workings days per week,
- Yearly shutdown periods of production sites and
- Vacation times.

Figure 5.22 shows an exemplary list with agility measures. The agility characteristic "capacity adjustment" is not outlined as this numbers depends on the overall production network and will be obtained by the material flow simulation.

The content and idea behind each agility measure can be the same for all the different agility levels, but they can differ in their aspirations according to the agility characteristics 'implementation speed' and 'adjustable capacity' as well as in terms of 'profitability'. An example would be the increase of the number of shifts at the production line of one production network partner from two to three daily shifts. In the setup with a current agility level, discussions with practitioners showed that it usually takes five months for its full implementation: The additional workers need to be identified, hired and trained. Then the start of the third daily shift requires no additional expenses besides the salary of the additional workers. In a setup with increased agility this same agility measure could

Network setups	Allocated agility measures	Capacity adjustment	Implement. time	Max. run time	Activation point	Variable costs	One-time costs	Fix costs	Invest-ments
High agility	• Overtime accounts with x h • Increase number shifts to x in department y • Outsource production content z • Define +/- x % quantity with JIS-Suppliers								

Figure 5.22: Exemplary list with measures combined to production network setups.

be realized during a reduced time frame of only three months. This would require additional investments and expenses, for example for additional fees for the hiring company to hire the workers quicker or additional expenses for more training efforts to reduce the required training time.

It is helpful to take an overall perspective on the production network during the process of identifying the agility measures. It should be noted that at minimum the first round of idea generation processes that sufficient measures be identified for the bottlenecks of the production network. The material flow simulation simulates the production network capacity. Therefore the identification of the agility measures can be described as a systematic search for the bottleneck of the production network. When the bottleneck which hinders the overall production network to adjust its output to the needs of the demand scenario is identified, concrete agility measures in terms of throughput or implementation speed can be searched.

In practice it appeared to be helpful to use the knowledge of the production planners and managers about the potential bottlenecks in the production network. Their experience and knowledge helped to identify bottlenecks with their identification by using the material flow simulation. With the identified bottlenecks available, the specific agility measures can be created and identified quickly.

To ensure their acceptance and reduce the effect of shifting bottlenecks it is important to discuss the agility measures with all of the production network partners. Capacity adjustments in the production of the focal company need to be communicated towards the suppliers in the production network. It is relevant to understand what measures are available on the supplier side to adjust their capacity to the requirements of the stressing demand scenario. These discussions cannot be conducted with the entire suppliers base due to the very high effort required. That is why a prioritization and selection of the suppliers is crucial while defining the scope of the production network as done in step one of the method, explained in section 5.2.1. Furthermore, it is helpful to start these discussions with the most relevant suppliers and the ones where the most trustful relationships

are established. From the practical experience the closely related suppliers are open for discussions and provide ideas and suggestions about how agility measures can increase the agility of the production network.
The identified agility measures are then combined into several production network setups, all with the assumption of different agility levels. The first production network setup is characterized by “current agility”. It consists of agility measures which are already available in the production network. These measures are the ones that the company and its affiliated production network would activate with their current knowledge and know how. This setup represents the status quo of the agility of the production network.
Another task of the agility stress test is to identify measures how to improve the agility of the production network. This means that it is necessary to identify agility measures which can be combined with production network setups having increased agility levels. These measures need to be achievable and realistic on the one hand and on the other hand ambitious enough to advance the overall agility of the production network.
Two experiences helped to overcome this issue: the involvement and expressed support by the top management and project sponsor and the definition of a network setup with a very ambitious and high agility level. The production network setups with the different agility levels are derived by following the iterative experimentation process introduced in figure 5.20. The results of the agility evaluation using the simulation engine show if the required agility level could be achieved. If not, the iterative process is repeated and additional production network setups with increased agility are derived.
The production network setups consisting of agility measures are input for the simulation engine. For each of the agility measures operational information are available.
For each of the production network setups an individual version of the simulation engine is created. By doing so it is ensured that the production network setups with their measures are represented in the material flow and profitability models. The created version of the simulation engine are used to experiment and evaluate their agility level. With the insights gained during the experimentation the agility of the production network setups can be adjusted to the requirements.

5.3.2 Execution of simulations runs

In the following it is explained how the simulation engine is prepared for the execution. Further the execution of the simulation runs is outlined. After collecting the agility measures and their description with operational information, the production network setups are integrated in the simulation engine.
The simulation engine needs to be prepared for the execution of the simulation runs. The course of the demand of the stressing demand scenario is provided as a production schedule in the material flow portion of the simulation engine. The created production

schedule in this context defines how many products are demanded by the customers of the focal company during the duration of the scenario. The production schedule triggers the production processes in the production network.

A correct representation of the production network setups with their agility measures needs to be ensured. Their collection with the different agility measures per production network setup as shown in figure 5.22 are the reference for the preparation of the models of the production network setups. For every defined production network setup an own version of the simulation engine model is created. The agility measures of a production network setup are transferred to the material flow part of the simulation engine model.

The material flow simulation contains random events such as probability distributions for break-downs of assembly lines. This is the reason why the simulation output is stochastic and therefore transient. Transient output "means that the distribution of the output is constantly changing" (Robinson 2003, p. 53). To obtain accurate results the output of the model needs to reach a steady state. Steady state means that the output is still varying, but it is varying according to a fixed distribution (Robinson 2003, p. 140). This characteristic needs to be taken into consideration when preparing for the simulation runs. Also the initialization bias needs to be reduced. The simulation models needs to find its rhythm. Robinson (2003, pp. 141–143) suggests two ways to handle initialization bias: either giving the model a warm up period which means to run the model until it reaches a realistic condition and start the data collection. Or to set initial conditions in the model right at the start of the run, for example placing work-in-progress in the model. For the material flow simulation a warm up period is included into the simulation runs. That way the model starts under realistic conditions.

Furthermore, the financial information about the agility measures needs to be transferred to the spreadsheets of the profitability model. It needs to be made sure that all the required financial data is available and transmitted to the profitability model. When the simulation engine is prepared with the required information, the execution of the simulation runs can be realized.

Before the execution of the simulation runs can be realized their run-length needs to be defined, mainly for the material flow simulation. Robinson (2003, p. 151) explains that the run-length needs to be long enough to ensure that sufficient output data is obtained from the simulation in order to achieve the model performance with adequate accuracy. In the case of a simulation engine, the run-length should be the same as the duration of the stressing demand scenario.

With the run-length defined, the material flow simulation can be started. As the profitability model requires input data from the material flow model, the material flow model is run first. The generated quantity of the produced products over the duration of the simulation run is used as input for the profitability model. Robinson (2003, p. 152) recommends to perform at least three to five replications to ensure sufficient output accuracy. During the simulation runs the production output of every production network setup is

collected. With these information available the profitability model can be filled and be run.
The results of the simulation runs are collected in output files of the material flow as well as profitability models.

5.3.3 Analysis and evaluation of production network setups

The generated data for the production network setup by running the simulation engine needs to be analyzed in order to understand its agility level. This is part of the iterative process of figure 5.20 to systematically evaluate the production network agility. Therefore in the following the target is explained. Further, the process to analyze and illustrate the generated data is described.
As mentioned earlier, the goal of experimenting with the simulation engine is to understand the agility performance of the production network setups by changing the agility measures as the input parameters of the simulation engine. To evaluate the agility performance, the target system of the simulation engine as the simulation model needs to be defined.
The approach of experimenting with the production network setups has two purposes: Firstly to quantitatively describe the agility of every production network setup and secondly to identify those agility measures that improve the agility of the production network. As the three key characteristics describing agility are the amount of adjustable capacity, the speed to adjust capacity and the resulting profitability, these characteristics represent the target system of the simulation model. As explained in figure 5.19 these are the results of the simulation model which can be influenced by the input. They need to be understood by learning from them to adjust the inputs. The inputs are the agility measures of the production network.
They need to be measured in order to provide an objective evaluation of the agility performance of a production network setup. Figure 5.23 illustrates the elements of the target system of the simulation model and provides the KPIs to measure them.

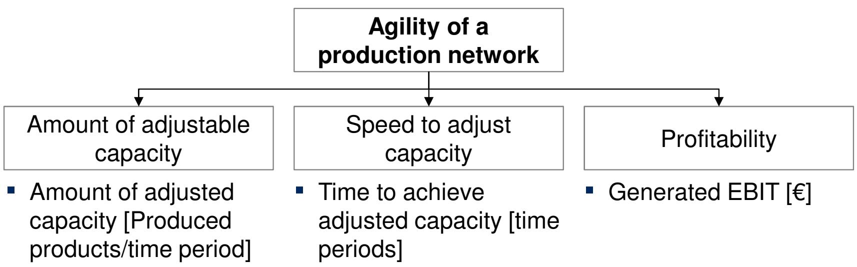

Figure 5.23: The target system of the simulation model with its corresponding KPIs to evaluate the agility of the simulated production network setups.

The goal is to assess how certain agility measures influence the agility of the production network. For that purpose the outcomes of the simulation engine, the evolution of the production output over time and the corresponding EBIT calculations need to be analyzed in detail. And if needed, the selected agility measures of a production network need to be adjusted or developed further. The approach which is applied in the course of this step is called "experimentation" and means to run "What-if" analyzes with the model simulation (Robinson 2003, p. 53). A process which is outlined in figure 5.19. Also Thomke (2003) emphasizes to use experimentation to gain understanding, not only while running simulation studies, but also to innovate towards finding new insights and technologies. The ideas of Robinson (2003) and Thomke (2003) are used as a guidance throughout the experimentation with the production network setups.
The idea of experimenting with the simulation engine, guided by the target system, is to compare the demand curve created by the stress test with the output curve of every production network setup. The output curve is called "agility curve" throughout this work as it describes how agile the output can be adjusted to the required stressing demand curve.
The agility level can be described as achieving the minimum of an area A which lays between two curves: the demand curve d(x) of the stress test and the corresponding agility curve a(x) of every production network setup. Mathematically, with t_x as the time periods, it can be expressed as:

$$A = |\int_{t_1}^{t_2} d(x) - a(x)\mathrm{d}x|$$

The agility measures are adjusted and selected the way that the shape of the resulting agility curve reduces the area between the agility and the demand curve. It is assumed that a production network setup with a higher agility level is capable of adapting closer to the demand curve than one with a lower agility level. Figure 5.24 illustrates this logic. The course of the stressing demand curve is set by the selected stressing demand scenario. The course of the agility curve of every production network setup can be influenced by the activated agility measures. The data to construct the agility curve is generated by the material flow simulation. Its output is the number of produced products over time as illustrated in figure 5.9.
Generally spoken the systematic adjustment of the agility curve to the demand curve is done by experimenting with the activation of different agility measures and checking how the resulting agility curve is aligned with the provided stress test demand curve.
With the aim of the agility curve the two agility characteristics amount of adjustable capacity and speed to adjust the capacity can be illustrated. The amount of adjustable capacity can be seen by the difference between the maximum and minimum amount of production capacity in the agility curve. The speed to adjust the production capacity can

be metered as the time it takes until the maximum or minimum amount of the capacity is reached.

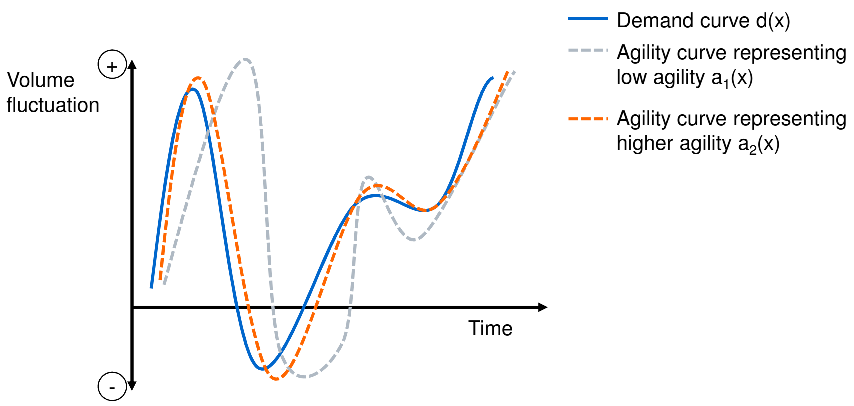

Figure 5.24: The distance between the stressing demand curve and the resulting agility curve of the production network setups needs to be reduced.

The third agility characteristic profitability is illustrated by the EBIT curve. It displays the course of the EBIT of every production network setup.
The illustrations agility and EBIT curves help to gain understandings about how the different agility levels are defined and how they can be influenced. It becomes especially transparent that an increased speed in capacity adjustment comes along with increased costs which reduces the resulting EBIT. The optimal balance between these two characteristics for every production network setup needs to be elaborated. This can be achieved by running experiments and adjusting the agility measures per production network setup and see how the speed of capacity adjustment and the EBIT react. If required, further analyzes of the EBIT-cost-relations can be realized. One possibility is the analysis of the development of the EBIT-margin over the time of the simulation run. This could generate insights regarding the development of the cost basis for production network setups with a higher agility level. These thoughts will be seen within the illustration of the agility evaluation discussed in the next section.
The production network setups are complex systems with dynamic and stochastic interdependencies. Direct cause-effect-relations of changes made to a production network setup cannot be seen directly. The material flow simulation helps to understand these cause-effect-relations. By systematically adjusting the used agility measures, the performance of the production network setup as a system of material flow elements can be understood. Critical production network partners which hinder the agility performance of the whole production network are seen as bottlenecks. Agility measures are defined to release these bottlenecks. It is expected that once a production process at a production network partner as the bottleneck is cleared, another production network partner appears as a bottleneck. This characteristic of highly dynamic bottlenecks is defined as shifting bottleneck as explained previously. To understanding how these relationships work, a constant simulation

effort of the production network setups is required.
The systematic adjustment of the agility curve of the production network to the demand is done by the following generic steps:

1. Comparison of the agility curve of a production network setup with the curve of the stressing demand scenario,

2. Analysis of the bottlenecks of the production network setup in the material flow using the available analysis tools of the material flow simulation software,

3. Consideration of new agility measures or adjustment (in terms of higher aspiration towards agility) the current measures, done in the project team of the agility stress test,

4. Description of agility measures with operational information,

5. Implementation or adjustments of agility measures in simulation engine and

6. Running of simulations and analysis of the agility curves, if required restart with step one

At the end of every simulation run the results, in terms of agility and EBIT curves of every production network setup, need to be illustrated. This helps to trigger the discussion within the project team about how to adjust the production network setups. The software used to realize the simulations provide various integrated functions to analyze the performance of the simulated production networks.
The results of the material flow portion of the simulation engine are illustrated with the agility curves and can be analyzed according to the two agility characteristics potential amount of adjustable capacity and the speed to adjust the agility curves to the demand curves. Figure 5.25 shows an example of an agility curve created with the results of the material flow simulation. This exemplary agility curve shows in a market increase scenario how fast the output of a production network setup with high agility can be adjusted to the requirements derived from the stressing demand scenario. As explained, the material flow simulation model takes the operational inter-dependencies of the different agility measures of the production network into account. If the appropriate agility measures are selected and activated, the speed to adjust the production output can be increased. This adjustment of the agility characteristic can be seen in the corresponding agility curve. Due to the different combinations of the agility measures in the production network setups and their optimization, the agility performance of different production network setups are diverse.
The analysis of the agility curves should always be done in connection with the corresponding EBIT curves of the production network setup. The analysis of the profitability of the production network setups provides the third agility characteristic. It needs to

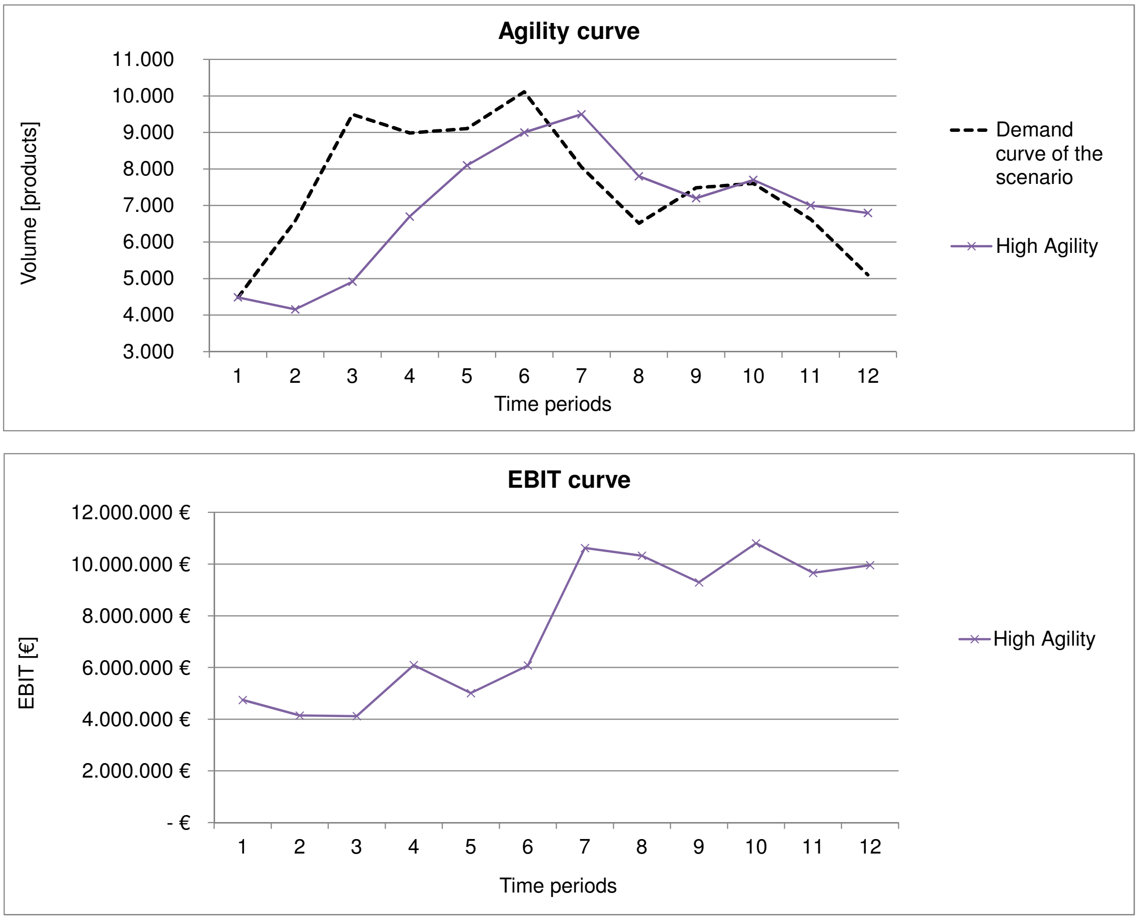

Figure 5.25: Illustration of an agility curve and a corresponding EBIT curve of a fictitious production network example.

be understood how much the EBIT of a certain production network changes with the different agility measures activated.

Usually agility measures which increase the agility of a production network along with the two agility characteristics amount of adjustable capacity and speed to adjust the capacity positively, require additional investments or operational costs. This has an impact on the EBIT of the production network setup. The additional costs need to be compensated by the additional revenue that can be generated as the output capacity can be adjusted quicker to the demand curve.

The course of the EBIT over a period of time is a result of the performance of the production network setups with its agility measures and hence their performance should be analyzed together with the agility curves. Figure 5.25 also shows the development of the EBIT for the same fictitious example as for the agility curves.

For the bottleneck analysis of the material flow in the production network setups the simulation software provides additional analysis tools. The software Tecnomatix Plant Simulation includes several standard tools that help to analyze the performance of the different production network elements as well as its performance as a whole network. The

tools include the “Bottleneck Analyzer”, different types of sankey diagrams as well as different charts and histograms to visualize the production network performance. Bangsow (2010, pp. 223–252) and Bangsow (2011, pp. 331–365) provide a broad overview of the available tools and statistics available in Tecnomatix Plant Simulation.
The result of this methodological step are insights about the agility performance of every production network setup:

- Agility curves, indicating the speed of capacity adjustment as well as its adjustable capacity dimension,
- The illustration of the EBIT development of every production network setup by the EBIT curve and
- a list of agility measures per production network setup which enable an implementation of an increased agility.

5.4 Insights

The last step of the developed methodology introduces how the generated results about the agility of different production network setups are illustrated. Moreover it will be explained which tasks are required to ensure a successful implementation of a selected production network setup. The overall goal of this step is to derive implementation steps to adjust the agility of the production network to the requirements of the focal company. In section 5.4.1, different illustrations are introduced of how the agility of the different production network setups can be presented. In section 5.4.2 it is explained how specific implementation steps can be derived to adjust the agility of the production network to the needs identified during the stressing demand scenario.

5.4.1 Presentation of results

The goal of this step is the illustration of the agility evaluation results. A transparent and clear illustration enables a comparison of the setups regarding the three agility characteristics “amount of adjustable capacity”, “speed to adjust this capacity” and “profitability”. It supports the derivation of conclusions about the current agility level of the production network and methods of how to adjust it to the requirements formulated by the management of the focal company. This information is used as input for the decision about what setups and measures will be implemented. Moreover the illustration can be used for the communication with the involved stakeholders to explain the results of the stress test and communicate potential adjustments in the production network to improve its agility.

The results of the agility stress test conducted in steps one to three of the methodology are:

- The performance of the production network setups according to the agility characteristics “amount of adjustable capacity” and “speed to adjust this capacity” illustrated by the agility curves enabling a “capacity” view on the production network setups. They are compared to the stressing demand scenario defined by the project team and the project sponsors.
- The evaluation of the production network setups according to the agility characteristic “profitability” symbolized by the EBIT curves.
- A list with specific agility measures per production network setup which were simulated in the simulation engine (see for example figure 5.22).

Figure 5.26 provides examples of agility and EBIT curves for a fictitious production network example. They illustrate the current agility level as well as two production network setups with increased agility levels. The underlying stressing demand scenario was characterized by a strong growth scenario.

Specifically the agility and EBIT curves are used to illustrate the agility performance of different production network setups. The two curves should always be analyzed together as both describe the agility concept for a production network in a precise way.
The agility curves explain how fast and to what dimension a production network setup can adjust its capacity in terms of produced volume to the stressing demand scenario. The speed can be read off by the time it takes until the production network's output reaches a certain level. This time can be measured in different time units such as days, weeks or months. The selection of the time unit depends on the type of the company, the product it produces and the industry it operates in. In general, for the agility characteristics “amount of adjustable capacity” and “speed to adjust this capacity” can be defined that the faster and to a bigger difference the output can be adjusted, the more agile a production network setup is. This consequently leads to a more precise adaption of the agility curve to the stressing demand curve. A closer adaption of the demand curve leads to more products sold and reduces the unfulfilled demand in case of a strong growth scenario. In case of a downswing scenario the potential over-production of a production network is reduced. To assess this potential financially, the EBIT curves are used.
As explained in section 5.3.3 the adjustment of the output dimension in combination with the high adjustment speed of the production network output is usually achieved with additional costs. In this case, the number of the produced products cannot be adjusted to the same scale as the costs, leading to increased unit costs. Unit costs mean the costs allocated to the produced units. Especially if more capacity flexibility is achieved by using agility measures such as additional external network partners (Rippel, Schmiester

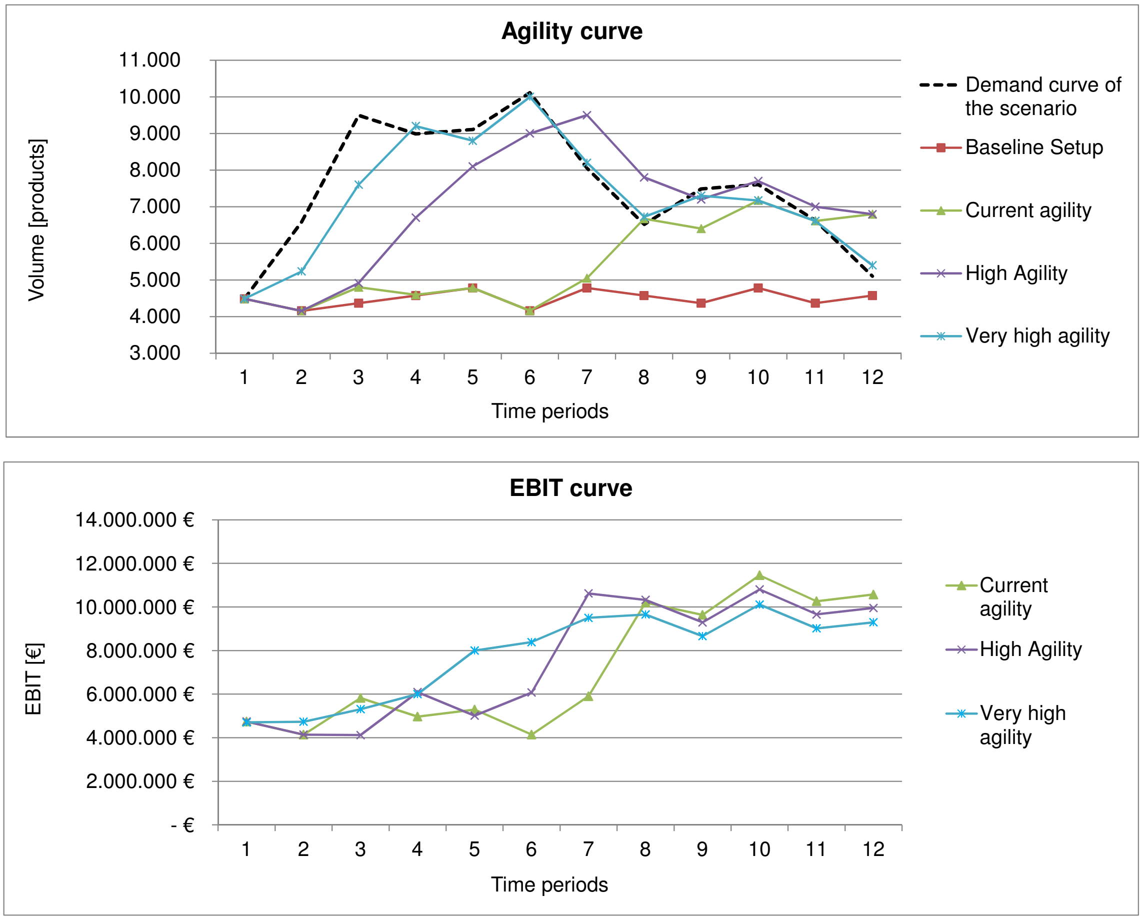

Figure 5.26: Exemplary agility and EBIT curves for current and two increased agility levels.

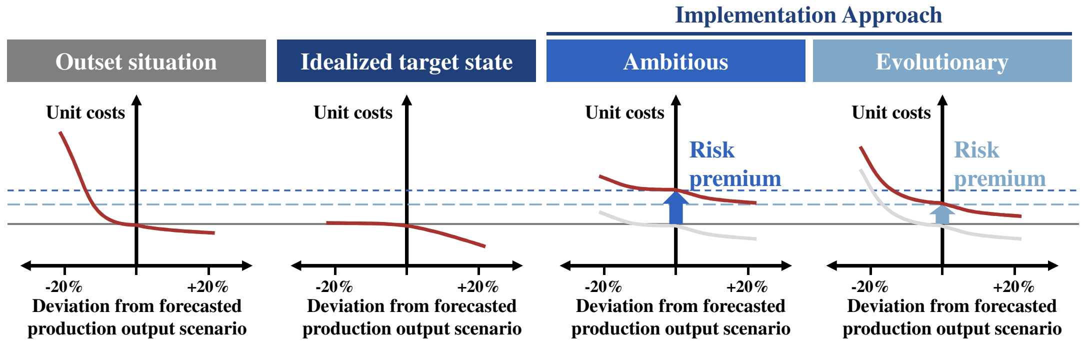

Figure 5.27: Illustration of adaption of unit costs and demand fluctuation (Rippel, Schmiester & Schönsleben 2015, p. 5).

& Schönsleben 2015, p. 5).
To assess how much additional profit can be realized by adapting the output faster to the required demand level achieved by using agility measures, the EBIT curve has to be analyzed. The EBIT curve of every production network setup takes the additional or avoided output in terms of sold or not sold products into consideration. Furthermore the additional or reduced costs to achieve the output are considered through the EBIT model. The thought that enabling an increased agility in terms of output capacity adjustment leads to higher unit costs of the produced products is also discussed in the Volume-oriented Changeability (VoC) concept (Rippel, Schmiester & Schönsleben 2015, p. 5). The concept discusses the finding that in case of an output increase, the unit costs decrease as the production assets can be used in a more efficient way. Whereas in a decrease situation, the unit costs increase more than the reduction of output volume as the cost basis cannot be adjusted as fast as the output decreases. This observation is also known as "sticky costs", especially for SG and A costs Anderson et al. (2003).
VoC describes that dealing with volatility and uncertainty of the demand can be handled by transferring the volume risk to third parties. This can be realized by integrating suppliers via outsourcing or buy-order-transfer models into the production network. However, the usage of the third parties can only be achieved by paying them a "premium" to have their capacity flexibility available. This premium consequently leads to higher unit costs (Rippel, Schmiester & Schönsleben 2015, p. 5). Figure 5.27 illustrates this concept by showing the change of the unit costs when volume fluctuations occur. Whereas in an idealized state the unit costs would stay constant when the output decreases and fall when it increases, the unit costs usually increase when the output drops. An ambitious implementation approach of the VoC concept would only increase the unit cost level, but would limit the unit cost increase during output reductions. In practical implementation the evolutionary approach is more realistic.

The agility concept discussed in this work additionally considers the speed of the output adjustment. For the illustration of the agility stress test results the illustration in figure

5.27 can be extended by the third dimension speed of capacity adjustment. Figure 5.28 shows the integration of the speed dimension. The illustration shows that production network setups can be available which enable the production network to adapt its output faster to changing demand, but result in higher unit costs. By transparently outlining this interrelation a management decision can be prepared and enabled. This decision refers to how the production network's agility should be positioned. One possibility could be the optimization towards a fast output adjustment which consequently leads to higher unit costs. Another one could be the direction towards limited unit costs, but a slower capacity adjustment. The illustration supports an understanding about towards what level and shape the production network agility should be developed.

The illustration aims to explain how much importance the speed of the capacity adjustment has and how it contributes to the overall agility. This contributes to the fulfillment of the stressing demand scenario. A higher speed of capacity adjustment enables a company to adjust the output faster to the demand. This capability contributes to the competitive advantage of a company compared to other competitors.

The extended VoC illustration provided in figure 5.28 only focuses on the cost side as the VoC illustration of figure 5.27. The additional revenue that can be generated when reacting faster to demand changes is not illustrated in the extended VoC illustration. Therefore it needs to be ensured that the EBIT of every production network setup is outlined in parallel.

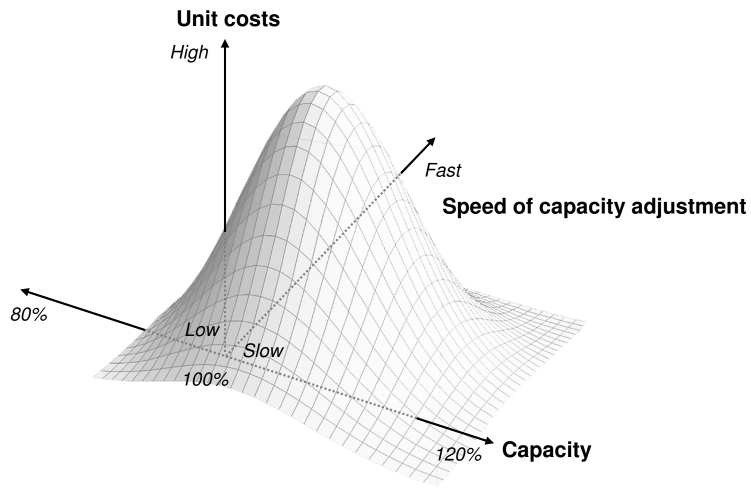

Figure 5.28: Illustration of the agility dimensions of capacity adjustment, unit costs and extended with the characteristic speed of adjustment.

5.4.2 Derivation of implementation steps

The objective of this section is to define what production network setup with its corresponding agility measures will be implemented in order to increase agility of the production network. The assessment of the agility of each production network setup, as discussed in the previous section 5.4.1, is used as a decision support by the management of the focal company.
To ensure a successful adjustment of the production network's agility, concrete implementation steps for the selected production network setups and its corresponding operational measures are defined.

Selection of the production network setups The production network setups evaluated according to their agility are a decision support for the (strategic) production management of the production network. As the focal company is the leader of the production network, its production management usually initiates the agility stress test. Therefore it uses the results of the agility stress test and derives the implementation steps. Two questions guide the decision:

1. What conclusions to take about the defined stressing demand scenario for their company and production network?
2. What production network setups should be selected to implement the agility defined by question one?

The first question deals with the judgment of the management about what uncertainty and volatility their company and hence their production network is facing. Approaches and methods how to evaluate and assess the uncertainties and volatility which are impacting the company can be used from literature.
The stressing demand scenario used for this methodology was derived from the past of the company and the industry it operates in. The assessment of the production network's agility was then evaluated based on the question:

> How well is the current production network prepared, if this historical scenario would happen again?

The management of the focal company needs to finally decide to what extent the production network should be adjusted for the historical scenario. This should be done by discussing the evaluation results for all the production network setups along their different agility levels. The management of the production network can come to the conclusion that the occurrence probability that the stress test scenario becomes reality is very low and hence the current agility level of their production network is sufficient. In the case

that a situation occurs with unexpected volatility and fluctuations, the situation can be managed by emergency management and ad-hoc decisions. An extensive preparation is not required. In this case no implementation effort is required.
The second questions is directly connected to the first one. The answer of the first question defines the boundaries for the adjustment of the production network.
Once a decision about the first questions is reached, the selection of the specific production network setups which will be used to improve the agility of the production network needs to be done. Based on the results of the agility evaluation, the selection of the network setups can be realized along the following criteria:

- Assessment of the occurrence probability of strong demand fluctuations - To what level of agility does the production network need to be prepared?
- Cost-benefit evaluation of the operational measures - What money is to be spent upfront to be prepared for potential events?
- What resources in the focal company and production network are available to ensure the implementation of the selected production network setup with its corresponding agility measures?

The production management in this context should not only consider the target system of agility for the simulation engine formulated in figure 5.23. Additionally, further factors should be considered to select the production network setup. These include factors which were not considered during the agility evaluation and can lead to target conflicts. They include:

- Financial targets besides the profitability orientation (for example cash-flow or financing targets, such as liquidity or working capital),
- Technical targets (for example targets of capability as well as product or machine design such as productivity, quality, machine dimensions or innovativeness) and
- Company culture targets (such as employee satisfaction and employer attractiveness consisting of employee motivation, market power on the labor market, social responsibility in the region etc.).

While selecting the potential measures to increase the agility of the production network, these target conflicts need to be discussed and solved by the management of the focal company.

Preparation of implementation of agility measures After selecting the production network setup with the required agility level by the management, its implementation needs to be ensured. A successful adaption of the production network agility can be achieved

by using tools to ensure a successful measure implementation. These management tools enable a structured planning and controlling during their implementation process. Within literature a selection of approaches and methodologies are available to realize a successful implementation in the production environment. Schmidt (2011, pp. 185–208), for example, provides a methodology for the implementation in production systems.
The implementation of the identified production network setup and agility measures needs to be prepared and planned appropriately. To achieve this goal, different techniques supporting the implementation are available. Schmidt (2011, pp. 185–208) mentions tools such as:

- The compilation of implementation plans for every operational measure to plan its required activities for implementation (including the definition of clear responsibilities, due dates etc.),
- The setup of a tracking system to control the fulfillment of the implementation plan and
- The definition of a KPI system to track the progress and achievements of a production system, for example in terms of an improved agility of the production network.

Further methods include the implementation of a steering organization, for example, steering committees at different hierarchical levels, to discuss the progress or potential problems that come up during the implementation. This is especially important as the implementation of the measures might require the interaction with several stakeholders, such as external network partners or partners from different production sites.

5.5 Conclusion

In the previous sections a methodology was introduced about how to evaluate the agility of a production network using a stress test approach. The concept of stress tests mostly used in the finance industry was transferred to the area of production networks. It was used to assess their agility.
The created methodology consists of four steps which enable a focal company of a production network to evaluate its agility. For this objective demand scenarios are defined which put stress in terms of strong demand fluctuations on the production network. The stressing demand scenarios are derived from historical demand courses with strong fluctuations. These reference time periods are characterized by strong macro-economic changes and financial turbulences.
To evaluate the agility a simulation engine consisting of two simulation models is used: The material flow within the production network is simulated using a DES-software. This

enables the assessment of the agility characteristics adjustable capacity and speed to adjust the capacity of the production network. The second model evaluates the profitability characteristic of agility based on an EBIT calculation. By using the simulation models for the assessment of the agility it is ensured that the relevant inter-dependencies of the agility concept are incorporated into the evaluation.
Different agility levels are then evaluated by experimenting with the simulation engine. Different agility measures can be integrated into the models and their impact on the agility can be assessed. This creates a holistic understanding of the agility performance of the production network. The performance is illustrated using agility curves and corresponding EBIT curves.

By applying the methodology a focal company is capable to evaluate the current agility of its production network. It furthermore can define specific agility measures to increase its agility. These agility measures can be simulated and evaluated according to their impact on the agility of the production network. The evaluation is done along the three agility dimensions adjustable capacity, speed to adjust the capacity and profitability. This way the focal company can quantify the agility and identify ways to improve. Tools such as the agility curves contribute to the ability to illustrate the agility of the production network.

6 Methodology validation

The developed methodology introduced in chapter 5 is validated during an application at an European contract manufacturer of cars. The validation was realized in the course of a research cooperation about agility in manufacturing. The cooperation has two objectives:

- Conducting basic research about agility in manufacturing and
- The derivation of practical concepts to implement agility in the company.

The second objective enables the application of the methodology in practice at the contract manufacturer.
The methodology was applied during a project with close cooperation between the representatives of the contract manufacturer, of its corresponding production network and the author. The recipient of the agility evaluation results was the CEO of the company as well as their company's Vice President of Manufacturing.
The project was realized under a non disclosure agreement that is common in the industry. This means that no real data could be used and disclosed in the outline of this validation. Therefore in the following simplified data without any direct reference is used. Nevertheless, the simplified data provides a rough orientation of the results.
In section 6.1 the company and its corresponding production network is introduced. Thereafter in section 6.2 a detailed explanation is provided of how the methodology was applied in the company. This chapter closes in section 6.3 with a discussion of the results and findings of the methodology application.

6.1 Introduction to the company

As the partner company operates within the dynamic environment of the car industry, the initial situation in general as well as its specific situation as a contract manufacturer will be explained. In the second part of this section, an introduction of the company and its related production network is provided.

Automotive industry and contract manufacturers

A short overview of the automotive industry is provided and implications for the partner company as a contract manufacturer operating exclusively in this industry are derived. Reasons will be explained for the need of agility research for the partner company.

In 2014 roughly 88 million cars were produced worldwide (Roland Berger & Lazard 2014, p. 9). The size of the worldwide automotive supplier market during that year was over 1,400 billion EURO (EUR) employing more than 4.5 million people by only the top 100 automotive suppliers. Approximately 110 billion EUR were invested in capital expenditures in the automotive supplier industry (McKinsey 2015, p. 4). The Compound annual growth rate (CAGR) ranging from 0.5 per cent in Europe to more than 9 per cent in NAFTA in the recent years (Roland Berger & Lazard 2014, p. 9). This collection of numbers shows the global importance and attractiveness of the automotive industry.
At the same time the car industry is facing significant challenges. They range from potential disruptive trends such as connectivity, autonomous driving and electrification articulated by McKinsey (2015, p. 14) on the product side to an increasing volatility and uncertainty as well as a strong competition on the market side (Roland Berger & Lazard 2014, pp. 4–5).
Additionally, the market side the automotive OEMs react by extending their product offering, increase the number of variants and intensify the cooperation with their suppliers. Wildemann (2015*a*, pp. 14–16) proves the increased number of car segments and derivates 1980 and today.
Uncertainty about the future market development remains high. Depending on the region the expected growth rates fluctuate significantly. The OEMs are expected to adjust their global production footprint shifting their focus to the growing emerging markets. Automotive suppliers react by consolidating and increasing their offerings towards the OEMs (Roland Berger & Lazard 2014, pp. 23–33).
The OEMs and suppliers need to react to these challenges by increasing their flexibility along their entire value chain (Roland Berger & Lazard 2014, p. 39). McKinsey (2006, pp. 4–5) expect to see highly flexible and process-stable car producers. A lever to increase this flexibility is the enhanced usage of contract manufacturers for cars by the automotive OEMs (McKinsey 2006, p. 11).
These identified challenges also influence the contract manufacturers of cars. They furthermore face challenges specific to their business.
Contract manufacturers are seen by the OEMs as a way to increase their flexibility of their production network. They can be integrated into an OEM's production network to manufacture niche models, to take over a ramp-out production or to fulfill demand peaks. Contract manufacturers take over a lot of production content almost as a "real" automotive OEM. Therefore they are also called Mini-OEMs, Complete Suppliers or

Tier-0,5-Suppliers (Wittek 2013, pp. 45–46). An overview of different cooperation in the automotive industry is provided in (Hensel 2007, pp. 256–261).
The business of contract manufacturers is characterized by a limited number of big single production orders. These orders include an arrangement for a relatively long time period. The contract duration is limited by the maximal lifetime of a car (Unzeitig 2014, pp. 170–172).
Contract manufacturers in the automotive industry compete with two groups of competitors at the same time about production orders. On the one hand they are challenged by other contract manufacturers and at the other hand with the production departments of the automotive OEMs.
These OEMs are at the same time their customers. Due to their own production know-how OEMs are able to use benchmark values for the assessment of quotes offered by contract manufacturers for the realization of contract manufacturing services. This results in an unfavorable information situation for the contract manufacturers compared to other calls for proposals, for instance, the sourcing of components. This characteristic puts strong pressure on the contract manufacturers to stay competitive. Unzeitig et al. (2013, p. 72) mention further factors that represent challenges for contract manufacturers:

- the offering of the required manufacturing flexibility to fulfill orders for different customers operating in mass and niche markets,
- handling the requirements and standards of different customers as well as
- controlling the depth of the in-house production of different customers and projects.

Unzeitig et al. (2013, p. 71) further underline that contract manufacturers in the automotive industry need to constantly find a way to handle different challenges: the complexity of different car types, models and customer structures, different value-adding levels and fluctuating utilization of the production assets.
Furthermore the OEMs tend to in-source manufacturing content of the production of their cars to increase the utilization of their own production capacities. This can be realized as they could improve the product flexibility in their production capacities. The OEMs are capable of producing an increasing variety of models in their own production capacities (Nieuwenhuis & Wells 2015, p. 213). This trend would offer for contract manufacturers the opportunity to provide the manufacturing services as agility services for OEMs during strong demand fluctuations.
Another challenge for contract manufacturers is the need to ramp up the production quickly once a project was won. The new product needs to be integrated into the existing manufacturing infrastructure with as little effort as possible. Additionally, the integration with suppliers, often defined by the OEM, needs to be realized within a short time (Ciravegna et al. 2013, p. 2484).
It is expected that contract manufacturers in the automotive industry need to handle

an increasing variety of products which leads to a growing complexity in production. Additionally an even faster time-to-market of new products will be required (Unzeitig et al. 2013, p. 83). These collected challenges can be faced by applying improved agility capabilities.

The partner company and its production network

The partner company is a European contract manufacturer which produces complete cars on behalf of different automotive OEMs. Besides the manufacturing of complete cars they offer other services for car OEMs and suppliers such as the development and design of car modules.
Unzeitig (2014, p. 172) explains that a contract manufacturer can operate in two business areas:

- as a mass producer with high production quantity and resulting low costs or
- as a manufacturer of niche models with specific customer solutions for a small market segment.

The partner company is specialized on niche products of higher level cars. The manufacturing at the partner company is concentrated on one production site. Their manufacturing services include all relevant production steps which are required to produce a car (Klug 2010, pp. 404–426). The production steps realized by the partner company are the body shop, a paint shop and a final assembly line. Whereas the paint shop is shared between all of the car models manufactured at the production site, the body shops and final assembly lines are individual for every produced model. These manufacturing areas are usually categorized as the core competences of automotive OEMs (Schindele 1996, pp. 74–75). This means that the contract manufacturer needs to ensure broad imposed secrecy among the different car models.
Within scope of the agility evaluation was the production network of two derivates of one car model. These two derivates are exclusively manufactured at the partner company. All the customer orders as well as the production planning of the cars is handled by the OEM. The manufacturing orders are sent by the OEM to the contract manufacturer which than manufactures the cars and ships them directly to the OEM's customers. This value chain can be characterized as a make-to-order system.
Suppliers deliver the required parts for the production of the cars directly to the contract manufacturer. There are two types of suppliers: One supplier group is selected by the OEM and the partner company has to work with them. The second group are selected individually by the partner company. Many suppliers have long-term relationships with the partner company. The contract manufacturer communicates with them depending on the delivery agreements. This ranges from JIS over stock parts to arrangements with long

distances suppliers. These different delivery agreements are a complexity driver.
The capacity offering by the partner company for the automotive OEM is arranged in a general contract agreement between the two companies. Potential requests by the automotive OEM to adjust the capacity at the partner company are discussed in regular tactical capacity planning meetings. If a capacity adjustment is required, a preparation phase of several months is contractually defined. During this period the partner company can only adjust its capacity on an operational level.

6.2 Evaluation of the company's production network agility

In this section the application of the stress test methodology to evaluate the agility of the production network of the partner company is explained. In the beginning, the application's objective is outlined followed by a detailed explanation of the methodology validation.

6.2.1 Application objective

The partner company faces a very dynamic environment in the automotive industry as explained in the previous section 6.1. Especially the required speed to react to demand fluctuations in the market as well as their OEM customers is in focus of the company's top management. They identified an increased agility of their production and the corresponding production network as a possibility to react to these challenges.
The reasons of the partner company to realize the agility evaluation effort were to assess their own agility including the agility of the production network, as well as to identify potential areas to improve it. As explained above, the company is part of a research project regarding agility in manufacturing. The development of the approach was realized under the cooperation between the company and the research institute, mainly driven by the research institute.
Furthermore the company's intention was to turn the abstract agility concept into action and to make it operational. In addition, they were interested in a system of KPIs to measure agility in their production. From their point of view this is the basis to understand and improve their own agility.
The development of the approach to evaluate the agility of a production network using a stress test approach was especially interesting for them as the approach could be developed based on their practical requirements. In a next step the approach can be completely transferred to their organization ensuring a deep know how transfer. As the company is strategically pushing efforts to digitize their production, a requirement for the

development of the approach was to include simulation tools into the approach.

6.2.2 Methodology application

For the agility evaluation of the partner company's production network, all the methodology steps outlined in chapter 5 and illustrated in figure 4.5 were performed. The process was realized for two derivates of one car model. The derivates are only manufactured at the production site of the company for one automotive OEM. Every car is produced based on an order issued by the OEM. The customers can order from a wide range of individual features, hence every produced car can be seen as unique.
As articulated above, the top management of the company wanted to evaluate the agility of their production and the affiliated production network. The evaluation should be realized for one product which represented over two third of the partner company's production volume in 2014.
The agility evaluation using the stress test approach was driven by the partner company. The results of the evaluation were prepared from the perspective of the partner company as the focal company of the production network.

Identification of historical periods and definition of demand scenarios

It was agreed that the production network of this product until tier-1 was integrated into the evaluation. The project team consisted of the head of production planning, the responsible person for the technology planning and the author of the thesis. The project team had access to required specialists of the different departments inside the company and to selected suppliers. The realization of the agility evaluation was sponsored by the company's CEO and Vice President of Manufacturing.
The goal was to evaluate the current agility level of the company. Further it was expected to identify and assess two additional production network setups with higher levels of agility. They were specified as production network setups with high and very high agility. These levels should be underpinned with concrete agility measures. The sponsors of the evaluation effort requested an agility evaluation for a strong growth scenario. They wanted to understand how well the partner company is prepared for a demand boom.
The identification of the reference time periods to realize the stress test was done by analyzing different parameters of demand fluctuations in the automotive industry. As the partner company is located in Europe, different market indicators of the European car market were investigated. As the experiences of the partner company with the demand fluctuations during the Financial Crisis within the period between 2008 and 2010 were still very present, it was agreed to select this time period as a reference. The Financial Crisis resulted in a major fluctuation of the demand in the automotive industry. A strong

decline in demand for cars in 2008 was followed by a strong demand increase in certain markets in 2009 (Roland Berger & Lazard 2014, p. 10). These developments were major challenges for the automotive industry and required agility capabilities to react to them. The car model for which the agility evaluation has been done, had not been produced during the time of the Financial Crisis. This means that no historical production data of this product was available. It was therefore agreed to use general demand data of the car market to create the reference demand scenario.
As the goal was to identify situations with strong demand fluctuations, the official numbers of car registrations in Europe as well as in the different European markets were analyzed according to their monthly fluctuations. The goal was to identify those markets with the strongest fluctuations of car registrations. The car registrations were used as an approximation of the produced cars during the time period. The length of the time frames which should be used as a reference was defined as twelve months. The reasons were that the reaction on demand fluctuations in the automotive industry within twelve months required adjustments in the production that are not limited to short term measures, activated by ad hoc efforts. It is further required to identify and prepare measures and activate them in a structured management process. At the same time during a duration of twelve months the demand of a car is still not influenced by the life cycle of a car. This means that within twelve months the demand for the car model is not reduced because it reaches the end of the life cycle and the customer interest declines. This limitation at the same time reduces the solution space as in practice the implementation of long-term measures, such as significant investments into production capacities, would be evaluated based on longer time frames.
The monthly changes of car registrations, expressed as relative changes month-on-month, of different European markets were analyzed and discussed within the project team. Figure 6.1 shows the numbers for the German car market during the Financial Crisis between 2008 and 2010.

Different time frames and markets were identified and investigated such as the European car market in general and besides the German market different specific markets such as Spain, Portugal and Italy. Also different time frames for the markets were investigated: an option was the strong decline due to the Financial Crisis between January 2008 and December 2008. Another one was the strong recovery, especially in the German market, after the Financial Crisis, starting in at the end of 2008. The project team decided to focus on the German market as it had a strong break-in, but also a strong recovery, due to the subsidy for new small cars paid by the government ("Abwrackpraemie"). The project sponsors decided to use the German car market as the reference indicator for the demand of the customers and selected the time frame between January 2009 and January 2010 as the reference time frame. This period is characterized by strong month-on-month growth of car registrations. It represents a strong growth scenario, after a very significant decline in customer demand due to the Financial Crisis. The scenario describes a more

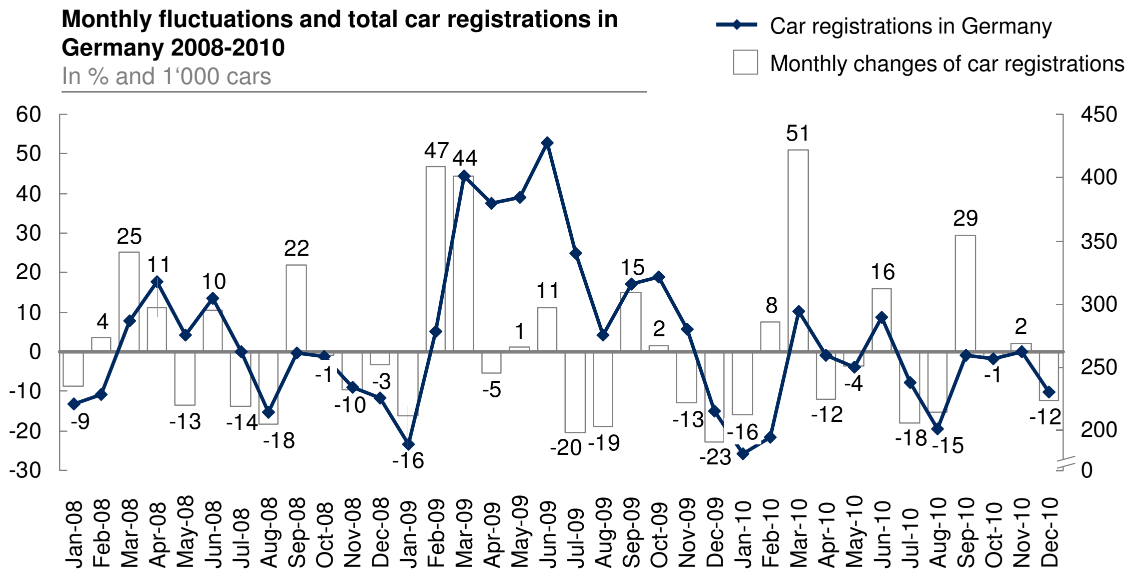

Figure 6.1: Monthly changes and total number of car registrations in Germany between 2008 and 2010 (German Federal Statistical Office 2015).

than doubling of the demand for the car model within five months. The selected demand scenario therefore represents a stressing demand scenario for the partner company and its production network. The fulfillment of this scenario would be a huge challenge for the partner company and required strong agile capabilities to fulfill it. The project sponsors wanted to understand and evaluate how agile the company currently is to react on this strong market growth. Furthermore, they wanted to identify specific measures of how to improve their agility.
The relative fluctuations per month were used as the basis for the creation of the specific stressing demand scenario for the partner company. As a starting base for the creation of the scenario, the average monthly production of the reference car model in 2014 was used. This average value was used as the initial value at the first month of the stressing demand scenario. The demand value of every following month of the scenario was calculated based on the monthly relative changes derived from the German car market. This approach led to a scenario which represents the strong demand fluctuations during the recovery after the Financial crisis, but adjusted to the production dimensions of the partner company. Figure 6.2 illustrates the derived demand scenario for the partner company.

The result of this first step of the methodology is a stressing demand scenario based on historical numbers applied to the situation of the partner company. The identified scenario represents strong demand growth within a twelve months time period. For the partner company and its production network it is challenging and stressful to fulfill the scenario.

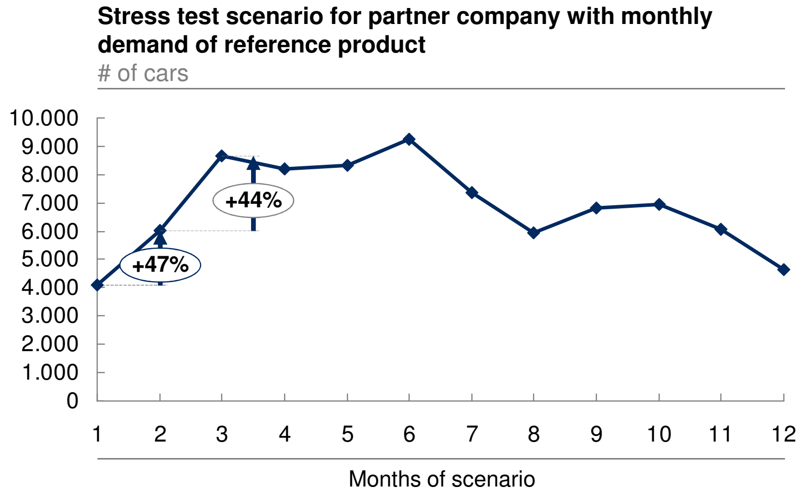

Figure 6.2: Resulting stressing demand scenario for the reference product [fictitious numbers, only magnitude representative].

Modeling and simulation of material flow and profitability

With the stressing demand scenario on hand, the next step for the project team was the creation of the models for the material flow and profitability simulation. The setting and delimitation of the investigation area as well as the definition of the model detail were the first definitions to make. It was essential to define to what extent the different suppliers should be included into the models.
To get reasonable results, the material flow model should consist of all the major internal process steps of the car production process flow. This included the simulation of the body shop and the final assembly. At the partner company a detailed material flow model of the paint shop already existed and was used for the production planning of the paint shop. This was the reason to consider the paint shop as a “black box” in the material flow model. The storage place for the car bodies which is placed in front (for the unpainted bodies) and after the paint shop (for the painted bodies) was integrated into the model.
To identify the suppliers which should be included into the material flow model, discussions with the supply chain department of the partner company were required. It turned out to be useful to include only those suppliers which deliver parts and modules on a JIT and JIS agreement. These suppliers will be called JIT- or JIS-suppliers in the following. They operate at the same rhythm as the partner company. The reason is that the lead times for the orders of the specific and individual parts and modules are so short that they need to operate in line with the focal company. This means that they use the same shift models and takt times as the “pace”-process of the focal company. They need to respond to changes in demand by adjusting their output quantity. Whether they are capable of increasing their output depends on their internal available capacity and the capacity of their supplier. Their internal available capacity is influenced by the throughput of their

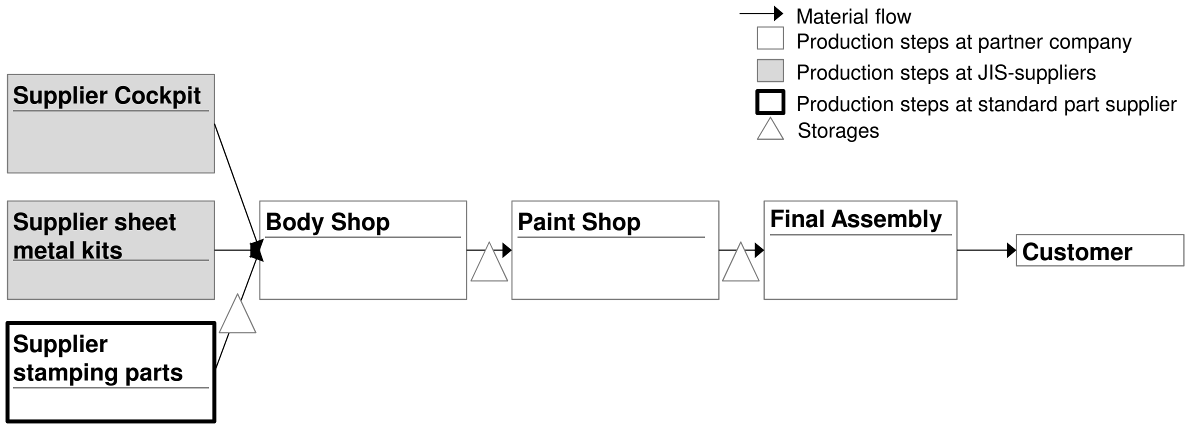

Figure 6.3: The production network in scope for the material flow simulation model.

assets (for instance, machines, assembly stations) and the availability of their personnel (for example, used shift model, usage of contract workers).
There are nine JIS-suppliers operating as tier-1 suppliers in the production network. They deliver parts which represent more than two thirds of the value of a car.
The close cooperation between the JIS-suppliers and the focal company needs to be investigated and understood deeply to assess the current agility and identify measures of how to improve the overall agility of the production network. On the other hand it was agreed that suppliers delivering standards parts are not included into the material flow simulation model. This delimitation was possible as the standard parts are supplied on a regular basis from mass suppliers. Therefore changes in the required quantities could be covered easier than for the JIT- and JIS-parts. The JIT- and JIS-parts are produced on request, synchronized with the production volume of the partner company. This means that an adjustment of their production volume required more preparation efforts.
After discussions with the supply chain management and within the project team, it was agreed that two JIS-suppliers that supply two parts in a JIS-agreement and one which was supplied in a standard way, meaning daily delivery not in sequence were selected. One JIS-supplier delivers the cockpit of the cars and the other delivers kits of different welded sheet-metal products. All of these JIS-parts passed through assembly processes at the suppliers site, including welding steps for the sheet-metal-parts, are individually combined for specific car orders and are delivered in sequence to the partner company. The supplied standard parts are stamping parts which are produced in batches at the JIS-supplier and are then delivered in boxes to the partner company. An overview of the production network in scope for the material flow model can be seen in figure 6.3.

With this process flow of the car production as well as with the selected parts and modules on hand a first conceptual material flow model was created. For the simulation the software tool Tecnomatix Plant Simulation from Siemens was used. The project team

could gather a good overview of the material flow within the production network.
The efforts for gathering detailed process data for a process flow with over hundred process steps (for instance, the body shop for the car model consists of over 70 processing stations) should be limited. For the creation of the material flow model it was agreed to summarize individual production steps in process steps and reduce the detail level. The reasons were that expert discussions with the production planners showed that the inter-dependencies between the different process steps and their impact on the overall agility could be understood from this detail level. This means that several process steps were aggregated in one simulation element within Plant Simulation. It was agreed that after this prototypical application of the methodology another run with more details can be realized, if required. As this attempt was the first time for the partner company to simulate the material flow of the whole production network including suppliers, it seemed practical to gather first experiences and findings about the required level of detail. For the same reason the simulation of the transport flows between the production network partners in the model was excluded in this first step.
To gather the required process data for the simulation of the internal process steps, the author conducted interviews with the responsible production managers. The interviews included the responsible production managers for the body shop, paint shop and final assembly of the cars. Further interviews were conducted with a human resources manager. The interviews contained detailed questions about the process flow, process parameters and the operation model. The required process data included information about the number of assembly and process stations, takt times, throughput times, Overall Equipment Effectiveness (OEE)-data of the machines (for example, utilization, breakdowns) and lot sizes. Required information about the operation model included the number of shifts, length of shifts and portion of contract workers. These information was gathered for every major production step of the car production process. The data was gathered under the assumption of a "regular mode" of operation. This means that no reactions to specific demand scenarios were considered. Information about the current agility capabilities were collected in a next step during another round of interviews. It was also discussed with every manager how the process steps can be aggregated in a pragmatic way to limit the efforts for the creation of the material flow model.
As explained above, the paint shop was treated as a "black box" in the material flow model. Therefore only information about the minimum and maximum throughput for the car model in scope were gathered. The responsible production planner estimated these information.
The required information to include the two JIS-suppliers into the material flow simulation was collected in two ways. Information about the cockpit supplier was collected in a detailed interview with the responsible supply chain manager of the partner company. As the goal was to represent this supplier as one material flow element, especially information about the operation model at the supplier's site were collected. For the sec-

ond JIS-supplier a site visit was conducted. The company delivers welded sheet-metal products just-in-sequence and stamping parts on a daily schedule. During the site visit interviews with operations managers were realized to gather the required information about the process flow, process parameter and the used operation model.
The gathered data and process flow was directly integrated in the material flow model. The preparation of a value stream map was not required as the agreed detail level of the material flow model as well as the overview knowledge and understanding of the process flow by the project team was sufficient.
The material flow model was structured along three levels: production management and steering, value stream and process data level. The production management level included methods to transfer the demand as input from the stressing demand scenario into the model, send orders to the different production network partners and to activate the different agility measures over the course of the scenario. The value stream level treated the connection of the material flow between the different production network partners. The material flow of the model was flowing directly from the suppliers to the production of the focal company. The data level contained all the operational information of the material flow components. Figure 6.4 provides a screenshot of the material flow simulation model of the production network.

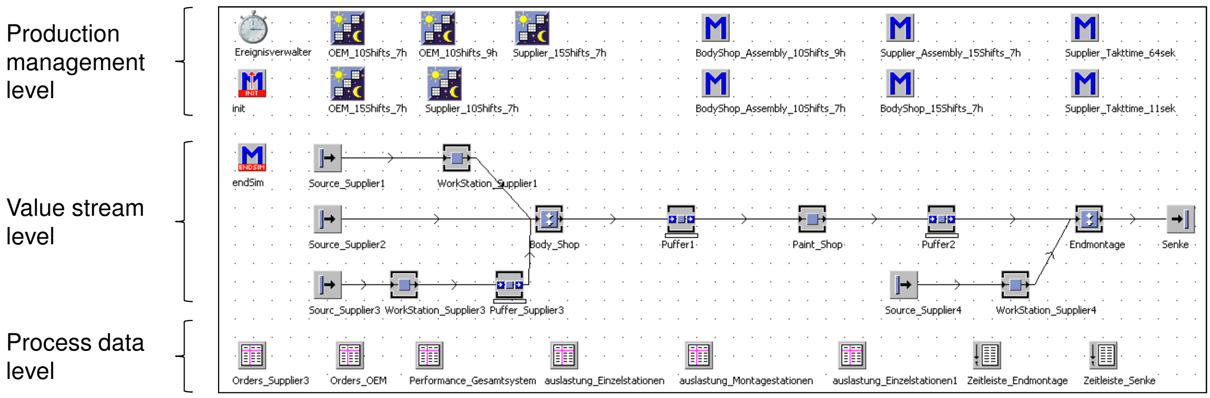

Figure 6.4: Screenshot of the created production network of the partner company.

The material flow model was validated and verified during the build up of the model in Plant Simulation by discussing and showing the model to the project team. The integration of the process data and the illustrations of the process flow was shared with the project team and with the involved production managers. Together with the project team members the method "structured model review", mentioned in section 5.2.2, was used to validate the material flow model. Additionally, the model was validated by comparing KPIs generated by the model with actual KPIs derived from 2014. These KPIs included the total production of 2014, monthly and daily production over the year as well as throughput and delivery date.
The profitability model, as the second part of the simulation engine was created by using

the software tool Excel from Microsoft. At first the profitability calculation was modeled conceptually using a rigid structure. Tabs with input data, calculation steps and resulting output data were used separately. This lead to the creation of the following major tabs in the Excel spreadsheet:

- Tabs with input data including main assumptions and the created daily production numbers of cars for the scenario duration derived from the material flow model,
- Tab with the summarized output data of the profitability model, meaning the expected revenue, corresponding costs and profits per production network setup and over the course of the demand scenario,
- Tab with the so called “SetUp Manager” which enables the activation of different agility measures per production network setup and evaluate its financial impact automatically as well as
- Different tabs to calculate the revenue and costs per production network setup with a bottom-up approach.

Figure 6.5 provides a screenshot of the collection of the main assumptions and the tab structure of the profitability model.

To fill the created conceptual profitability model in Excel, the author conducted an interview with a manager of the accounting department who accompanies the financial planning as well as the controlling of the car project in scope. Different financial information was collected to ensure a reasonable evaluation of the corresponding costs and generated revenues of the production network in scope. Due to imposed secrecy which is especially strict in terms of financial information, the project team had to roughly assume several financial numbers. In order to be clear about every number, which was assumed, it was highlighted in the profitability model. The expected revenue per produced car is an example for an assumed information. The real revenue numbers per car which were paid by the OEM were not disclosed. This information was calculated using an assumption of the profit margin per car. This margin was then added to the total costs per car which could be calculated using a bottom up approach.
The created profitability model was constantly validated and verified. At the end of the creation process a deep discussion with the project team and a representative from the accounting department discussed the profitability model in detail. The two models for material flow and profitability were the result of the second methodological step.

Profitability of agility at partner company - INPUTS

Revenue Inputs			
Input		**Units**	**Source**
Total costs per car	x	l	Interview Accounting
Profit margin	x	%	Assumption

Cost Inputs			
Input		**Units**	**Source**
Average yearly costs per body shop employee	x	l	Interview Accounting
Average yearly costs per assembly employee	x	l	Interview Accounting
Average supplied parts costs per car	x	l	Interview Accounting
Average labour costs per car	x	l	Interview Accounting
Portion labour from labour costs	x	%	Interview Accounting
Portion material from labour costs	x	%	Interview Accounting
Average transport costs per car	x	l	Interview Accounting
Basis volume for fix costs per year	x	#	Interview Accounting

Input for evaluation of measures			
Input		**Units**	**Source**
One time costs to recruit body-shop-employees 1 month faster (training, marketing etc.) [l/employee]	x	l	Assumption
One time costs to recruit assembly-employees 1 month faster (training, marketing etc.) [l/employee]	x	l	Assumption
Additional costs for night shift	x	%	Interview Accounting
Additional costs for Saturday shift	x	%	Excel-Dok Mr. Perl (Controller)
Additional costs for Sunday shift	x	%	Excel-Dok Mr. Perl (Controller)
Additional costs for sourcing JIT/JIS parts with >+/- 25 % qty.	x	%	Calculation
Additional costs for sourcing JIT/JIS parts with >+/- 40 % qty.	x	%	Assumption
Additional costs for sourcing norm parts with >+/- 25 % qty.	x	l	Interview SCM
Additional costs for sourcing norm parts with >+/- 40 % qty.	x	l	Interview SCM
Portion norm parts (by qty)	x	%	Interview SCM
Portion JIT/JIS parts (by qty)	x	%	Interview SCM
Portion norm parts (by value)	x	%	Interview SCM
Portion JIT/JIS parts (by value)	x	%	Interview SCM
Portion material costs at suppliers	x	%	Interview SCM
Portion fix costs and depreciation at suppliers	x	%	Interview SCM
Portion labour costs/valued added at suppliers	x	%	Assumption

Intro / INPUT Raw results Simulation / **INPUT General** / SetUp Manager / OUTPUTS / Cor

Figure 6.5: Main input data for the profitability model as well as major Excel tabs.

Agility evaluation of production network setups

The validated and verified material flow simulation model of the production network was created for a "normal" operation mode. Normal in this context means that the production network and its corresponding production steps operate in a stable and average performance state.

This step of the methodology aimed to evaluate how the production network would react to the stressing demand scenario. The project team and the project sponsors agreed to define a production network setup with the current agility level and two production network setups with increased agility levels. Besides the network setup with the current agility level, the other two were named high agility level and very high agility level, representing a very ambitious agility level.

To create the production network setups specific agility measures had to be found. To know how the different network partners would react to a stressing demand scenario such as the one specified in figure 6.2, another round of interviews with the responsible managers was conducted. The relevant interviewees were the responsible managers from the departments mentioned above, the production planner of the supplier of the sheet-metal kits and stamping parts as well as the supply chain manager responsible for the supplier of the car cockpits. During the interviews the stressing demand scenario specified in figure 6.2 was used as the reference. The following questions were asked:

- What operational measures are currently available to fulfill the stressing demand scenario? And how are these measures characterized in detail?
- How can these measures be even more ambitious according to agility and what effects would it have, especially financially?
- What would be further potential measures, that are currently not available, to fulfill the stressing demand scenario even more?

Within the discussions the responsible managers most often mentioned labor related measures to react to the stress test demand scenario. These included agility measures such as different shift models, using over-time, integration of contractual workers. Potential further measures to increase the agility of the production network were discussed in the project team.
Open and helpful discussions with representatives of the production network partners unveiled measures of how they can adjust their output quantity. It turned out that operating at the same pace as the focal company helped the JIS-suppliers to react to the increasing demand required by the focal company. The suppliers would react with identical measures as the focal company, which means that measures in the labor area would be their first priority too. Especially measures to adjust the number of shifts, for instance from 10 shifts per week to over 15 shifts and up to 18 shifts could be potential measures to increase the output.
Based on the contractual agreements between the focal company and the suppliers demand fluctuations of +/- 10 percent ad hoc were possible. Bigger demand increases needed a lead time of six months which is standard in the automotive industry according to the supply chain manager. This limitation in the production network turned out to be a major limiting factor of the production network's agility. A reason for these rigid limitations could lay in the efforts to implement lean principles in the supply chain. The goal was to reduce waste and hence inventory in the supply chain. These requirements could only be achieved by ensuring a stable and balanced production without major short term throughput fluctuation.
Another interview with the responsible person of the accounting department appended additional financial information for the economic impact evaluation of every measure. Also more detailed information about the evaluation of the different labor related measures were required. All the operational measures were collected and grouped into the

Network setups	Allocated agility measures	Capacity adjustm.	Implement. time	Max. run time	Activation point	Variable costs	One-time costs	Fix costs	Invest-ments
Base-line	• No agility measures • No demand shaping								
Current agility	• Overtime accounts x hrs	x cars/wk.	x months	x months	month x	-	-	-	-
	• Increase shifts in body shop and assembly to x	x cars/wk.	x months	-	month x	x €	-	-	-
	• JIS-Suppliers +/- x%	x cars/wk.	Ad hoc	-	month x	-	-	-	-
	• JIS-Suppliers >+/- x % .	x cars/wk.	x months	-	month x	-	-	-	-
High agility	• Overtime accounts y hrs.	y cars/wk.	y months	y months	month y	-	-	-	-
	• Increase shifts in body shop and assembly to y	y cars/wk.	y months	-	month y	y €	-	-	-
	• JIS-Suppliers +/- y %	y cars/wk.	Ad hoc	-	month y	-	-	-	-
	• JIS-Suppliers >+/- y %	y cars/wk.	y months	-	month y	y €/part	-	-	-
Very high agility	• Overtime accounts z hrs.	z cars/wk.	z months	z months	month z	-	-	-	-
	• Increase shifts in body shop and assembly to z	z cars/wk.	z months	-	month z	y €	-	-	-
	• Invest into paint shop capacity	z cars/wk.	z months	-	month z	-	- -	- -	z € -
	• JIS-Suppliers +/- z %	z cars/wk.	Ad hoc	-	month z	y €/part			
	• JIS-Suppliers >+/- z %	z cars/wk.	y months	-	month z				

Figure 6.6: Overview of the production network setups with different agility levels and specific agility measures for the partner company.

three production network setups mentioned above. The operational specifications along the required operational information were collected and outlined as well. Figure 6.6 gives an overview of the collected production network setups and its operational information including its financial evaluation.

With information for every production network outlined in figure 6.6 available, for every network setup a version of the simulation engine was created. This was done using the validated baseline simulation model as the starting point. The different agility measures per setup were integrated by adjusting the baseline model with the new operational measures. As the potential agility measures to react to the stressing demand scenario were mainly labor related, especially the production management and steering level of the material flow simulation was used to integrate the agility measures. The verification and validation of the created simulation engine versions were done by demonstrating and discussing each one with the project team members. Cross and sanity checks of the models themselves as well as the results were done within the project team. Another validation step was realized by comparing the production numbers of another car model (not in the same product category) during the same selected reference period between January 2009 and 2010. It could be seen that for the production network setup with the current agility level the same direction, an increase, was realized.

The simulation engine produced the agility curves and the closely related EBIT curves which are both shown in figure 6.7. The two curves were used as the target system to optimize the production network setups according to their agility. The goal was to find optimal definitions of every production network setup by balancing out the course of the agility curve to be as close as possible to the demand curve. On the other hand ensure a maximum of EBIT at the same time. Different compromises had to be made.

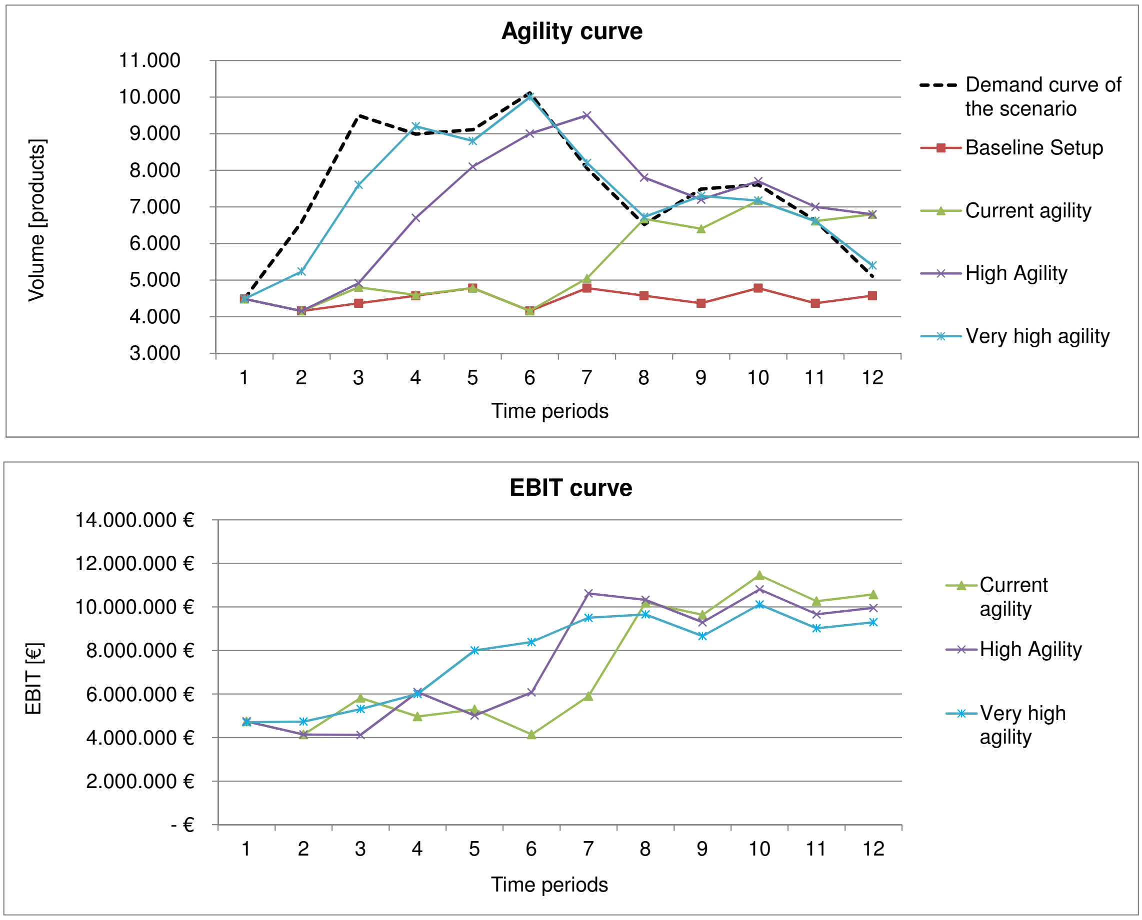

Figure 6.7: Agility and EBIT curves created for the example company [fictitious numbers, only magnitude representative].

The improvement of every production network's agility was done by experimenting with the production network setups. Therefore simulation runs using the simulation engine of every production network setup were conducted. The resulting agility and EBIT curves were than analyzed. Additionally, different KPIs, such as the throughput of every production network partner were analyzed to gain insights for the experimentation. Additionally, analysis tools available in Plant Simulation were used to gain more insights about how agile the production network setup is and how agility measures can be adjusted to increase the agility according to the required levels. New agility measures to increase the agility of the production network were identified as well.
An example of the internal software tools of "Plant Simulation" is the "Bottleneck Analyzer" which was used to identify bottlenecks in the process flow of the production net-

work. In the event that a bottleneck could be identified, specific agility measures could be thought of to reduce it and hence increase the overall agility of the setup. In this case, new insights about a specific bottleneck could be gained, and agility measures to eliminate it were discussed during follow up interviews with the responsible managers or inside the project team.

It was especially challenging to identify agility measures in the network setup with a very high agility level. For this setup measures were required which are very challenging and often outside the approach as it is done today. The change of the manager's and the project team's mindset to identify measures to increase the agility was difficult. In the past their mindset was focused to waste reduction in the production and supply chain which often goes with reducing inventory and ensuring a stable and foreseeable production. The thinking of measures to increase agility which often included the acceptance of additional costs was problematic.

The approach outlined above was done as a sensitivity analysis by adjusting the measures of the production network setups, transforming them to the simulation engine and analyzing the generated data output and the different bottlenecks. While adjusting different agility measures and observing how they impacted the production network's agility performance, insights about the agility performance of the production network could be gained.

During the experimentation it turned out that the current agility level needed too much time to adjust the output to the required demand of the stressing demand scenario. Different existing agility measures were adjusted under the aspect of helping to increase the output of the production network faster. An example is a faster integration of additional shifts at the different production network partners. In the production network setup with the current agility level it took five to six months to implement an additional daily shift. Assumptions were made how it could be realized within four, for the setup with high agility, or even three months in the very high agility setup. These adjustments could be realized with higher financial efforts, for example with higher recruiting fees due to a more intense search, the payment of transfer fees or spending for additional training efforts to on-board the additional employees faster. These additional expenses were also reflected in the profitability simulation leading to higher costs per car produced. Further ideas of the project team to speed up the output increase included measures to outsource production content to be able to increase the takt time without investing in infrastructure. These ideas were also evaluated using the simulation engine but turned out to be too expensive and hence were excluded.

The financial evaluation of agility measures which required the cooperation of suppliers was difficult. Whereas the operational evaluation of potential agility measures in terms of an output increase of the supplier could be openly discussed with the responsible managers, judgments about the financial impact of the agility measures could not be received. Reasons were the very hard and intense price negotiations between the contract manufacturer and the suppliers representative for the automotive industry. The supplier did not want to influence its negotiation position negatively with the publication of price estimations of potential agility measures. Therefore the financial evaluation of the measures needed to be done by estimation. Internal know-how of the supply chain department about the cost-breakdown of parts and modules was used to create reasonable estimations. The estimations were created in the project team and checked back with the supply chain department.

The end result of this step were three different production network setups which were evaluated according to their agility. The agility and EBIT curves in figure 6.7 illustrate their agility performance.

Derivation of insights

The results of the evaluation of the three different production network setups with their different agility levels were presented and discussed with the project sponsors. Input and basis for the discussion were the agility and EBIT curves illustrating their agility performances as shown in figure 6.7. During the discussion the impact of the speed of the output adjustment and its impact on the EBIT, especially in an upturn scenario, was discussed. It could be shown that specific agility measures are available to increase the agility of the assessed production network. The production network setups with the increased agility levels could fulfill the stressing demand scenario better and generate additional EBIT. This was due to the increased speed of production ramp up resulting from the specific agility measures which were part of the production network setups. The related additional costs could be over-compensated by the additional revenue that could be generated earlier in the scenario due to faster customer demand fulfillment. The financial impact in terms of additionally generated EBIT for the network setups with high or very high agility over the scenario course was significant, especially compared to the EBIT generated with the production network setup with the current agility level.

The project sponsors mentioned that an important difference between the production network setups was the requirement of investments: Whereas the production network setups with the current and high agility level could realize the capacity adjustment without any additional investments, the setup with the very high agility needed significant investment into a production asset. As the uncertainty about the utilization of expanded assets in the future are difficult to assess, the sponsors favored the network setups which did not require investments.

The evaluation also demonstrated that the agility measures for the capacity adjustment inside the company can be activated faster than the agility measures within the production network. This means that an increased overall agility of the production network cannot be fulfilled by the production management limiting only on internal agility measures. Agility measures towards the production network needed to be included in the

efforts as well. Usually the management of the production network is not represented by a dedicated department, hence the supply chain management or the sourcing department need to be included in the efforts to increase the production network agility.
Detailed plans and ideas how to realize the implementation of the agility measures were brainstormed and discussed. The elaboration and concretization of these specific implementation steps need to be done in cooperation with the responsible departments. For the proposed measures and for the increased agility within the production network, the result was to include an increased speed of capacity adjustments in the contract discussions with the suppliers. Ideas to include possible call off fluctuations which are broader than the current ones were discussed. Concrete implementation steps were not defined during the evaluation, however, the findings were directed to the responsible departments for concretization.
The results of the agility evaluation as well as the created stress test methodology were successfully handed over to the partner company. Concrete implementation steps were not yet defined, but the derived findings are integrated into their strategic pathway to increase the company's agility.

6.3 Conclusion

In the previous section the application of the methodology to evaluate the agility using a stress test approach on a exemplary company and its production network was described. It was proven that the methodology can be used successfully in practice to make the agility evaluation of a production network operational. Furthermore it was shown that setups to increase the agility of the production network could be identified and evaluated according their adjusted fulfillment of the stressing demand scenario.
To show the practical relevance of the methodology, the production network of a contract manufacturer operating in the automotive industry was assessed. Therefore a stress test demand scenario with a strong upturn derived from the demand development of the German car market between January 2009 and January 2010 was created. Available agility measures as well as further potential measures, summarized in the production network setups, were evaluated according to their agility to fulfill the stressing demand scenario.
The application unveiled that especially the agility characteristic 'speed of capacity adjustment' is the main driver to react to a stressing demand scenario. The usual corresponding additional costs can be compensated by additional EBIT. The approach enables a holistic financial evaluation of setups with increased speed of capacity adjustment, the corresponding additional costs and the additional generated EBIT.
The methodology enabled a quantitative evaluation of the production network agility. A set of three specific KPIs was used to describe it. With the KPI set available different production network setups could be compared with each other regarding their agility.

Furthermore the methodology facilitated an overarching understanding of the production network agility. With the usage of simulation models a deep understanding about the inter-dependencies of the production processes at the production network partners could be gained. Further the inter-dependencies influenced by the different agility measures could be investigated in detail.

By applying the method it could be demonstrated that the company's agility was not limited by its internal agility. The company should also think about measures to increase the agility of their production network partners. Especially the limitations to adjust order quantities ad-hoc by only plus/minus ten per cent and for greater fluctuations a lead time of six months limited the production network agility. This could be solved by discussing a broader range of demand fluctuations with the production network partners and adjust the relevant contracts and agreements accordingly. These insights about the relevance of the suppliers for the agility of the partner company was unclear upfront and could be proven to be relevant. Therefore it is necessary to include the supply chain as well as the sourcing department of a focal company into the efforts to improve the overall agility of the production network. The experimentation with the simulation engine of the production network helped the involved project team to understand the hinderers of the production network agility. For the top management of the focal company especially the financial evaluation of different production network setups with the EBIT was insightful. Based on the generated insights they could derive strategic measures to adjust the production network agility.

The usage of agility measures to adjust production capacities quicker are challenging for the implementation by operational management. Potential implementation hurdles need to be considered by the responsible top management. An example for these hurdles can be an increased stress level of the operations team to implement the agility measures.

The methodology uses a top down approach to evaluate the production network agility. It is very useful to show and assess the potential of agility which can be achieved on a production network level, especially in financial terms. On the other side a discussion was going on about the level of detail which was used in the evaluation steps. A weighing of the efforts and benefits needs to be done regarding increasing the simulation model detail with its corresponding efforts and comparing it with the additional insights which can be generated. Also the financial evaluation of the production network setups can eventually be detailed as well. The advantage of the approach is that it can be detailed and extended when needed.

7 Conclusion

In this closing chapter a summarization and reflection of the research effort at hand will be given. It will be assessed if the methodology to evaluate the agility of a production network using a stress test approach developed in this thesis can be used to answer the research question. For that purpose, the evaluation characteristics to ensure the newness of the research effort introduced in chapter 2.3 are checked according to their fulfillment. For this objective, section 7.1 provides a summary of the thesis. Further, the evaluation characteristics are checked regarding their fulfillment. Section 7.3 discusses the results of the research effort and provides an overview of prospective research avenues.

7.1 Summary

Chapter 1 discussed the problems of companies lacking a methodology to evaluate the agility of their production network. In parallel, within the banking sector the stress test concept is used to assess the resilience of portfolios against system risks. The idea to use the stress test approach to evaluate the production network agility was the starting point of this research effort.

For its realization the research question about how a methodology should assess the agility of a production network using a stress test approach was set up. This research question was divided into sub-research questions which formed the basis for the development of the methodology.

Chapter 2 introduced definitions of basic terms used throughout this thesis. Further different concepts about how to react to changes in production were distinguished and the research focus was defined. Based on the research question, its sub-questions and the defined research focus evaluation characteristics were identified to ensure the newness of the research effort.

In chapter 3 these evaluation characteristics were used to assess the current state of research about methods to evaluate changeability of production as well as the usage of stress tests in the production environment. It could be confirmed that currently no methodology is available which evaluates the agility of a production network by using a stress test approach.

In the fourth chapter the theoretical frame for the methodology was established. This

included the identification of main agility characteristics, the introduction of an agility definition used throughout this thesis and the derivation of the stress test aspects which could be transferred to the production environment. Further the application area as well as the assumptions of the methodology were identified. Based on these definitions, the structure of the methodology consisting of four steps was proposed and introduced.
The four steps of the methodology to evaluate the agility of a production network using a stress test approach were explained in detail in chapter 5. A stressing demand scenario for the company is identified in step one. In the second step, a simulation engine modeling the companies production network is created. It consists of a material flow model and is completed by a profitability model of the production network. In the third step the simulation engine is used to test the agility of the production network. Therefore different agility measures are bundled into production network setups. These production network setups are evaluated regarding their agility level. The fourth step illustrates the results of the agility evaluation and derives implementation steps.
The validation of the methodology was realized by a practical example explained in chapter 6. It could be shown that the developed methodology can be applied successfully in practice. The application of the methodology to evaluate the production network agility of an European contract manufacturer of cars showed that an improved agility level leads to increased profitability. Specific measures were identified, evaluated and tested to improve the agility of the production network.

7.2 Discussion

Further the evaluation characteristics identified in chapter 2.3 are used to check if the methodology developed in the outline of this thesis answers the research question.

- **Holistic evaluation of agility:** The methodology evaluates the agility of a production network along three characteristics, with one of those being profitability. This means that the methodology provides a broad evaluation of agility in manufacturing, including an economic characteristic. The quantitative evaluation with the fourth characteristic pro-activity was not included.
- **Production network with focal company:** The methodology was developed for the agility evaluation of a production network. The focal company triggers the execution of the methodology.
- **Stress test based approach:** The stress test approach was transferred to the production environment.
- **Tool for production management:** The methodology needs to be realized by the production management of the focal company. Therefore, it is ensured that the

production management has influence on the objective setting and result derivation. Further an illustration of the agility evaluation of different production network setups is provided.

- **Quantitative evaluation of agility:** The agility is evaluated along three characteristics and for each agility characteristics a specific, operational KPI is provided.
- **Evaluation of inter-dependencies:** The methodology uses simulation models to evaluate the material flow of the production network as well as its profitability impact. Simulation models are built to assess the behavior of a system with different elements. Therefore when applying the methodology their inter-dependencies can be tested and evaluated.
- **Identification of improvement areas:** The methodology evaluates the agility of production network setups. The combination of the production network setups is completely flexible. For that reason different setups can be defined, tested and evaluated. By doing so, their agility can be improved gradually.
- **Practicality in different industries:** The application of the methodology can be shown in practice for an European contract manufacturer of cars. The applicability in further industries was not shown.

The methodology developed in this thesis fulfills the evaluation characteristics which were also used to ensure the newness of the research effort. Therefore it could be shown that the methodology provides an answer to the research question.

7.3 Outlook

This thesis provides a novel methodology to evaluate the agility of production networks. This was realized by transferring the stress test methodology from the financial industry to the production environment. In the course of the methodology development starting points for future research efforts could be identified.
The stress test methodology used in this thesis focuses only on demand fluctuations as one change driver. Other drivers such as technology changes which impact a production company are not part of the agility evaluation. Nevertheless, a production company needs to prepare for changes similar those as well. For that reason the extension of the methodology to include stressing scenarios of other change drivers as well can be part of future research efforts. The creation of an integrated simulation model including the environment with its changes and the production network could be an overarching goal. The analysis of the impact of different risk factors by simulating its consequences and potential mitigation efforts would be the result.

The methodology uses a limited number of specifically selected demand scenarios which represent the stress test scenarios. This means that not all potential developments and extreme events can be covered. That is why a starting point for future research could be the creation of a significant number of scenarios by using a Monte-Carlo-Simulation. Insights can then be derived from how many of these numerous scenarios can be covered by specific production network setups.
The characteristic of a stress test is that they are only capable of evaluating developments from a backwards-looking perspective, as discussed by Taleb (2014). He states that a statement about the preparation for new challenges and uncertainties potentially arising in the future is not possible (Taleb 2014, p. 50). This insight need to be investigated. Potential approaches using a Big Data approach to monitor the environment are arising. Heldmann et al. (2015) introduce an approach to analyze different indicators using the Big Data thinking to derive insights about future developments.
The usage of the simulation software calls for extension as well. The introduced methodology using a DES-based approach enables a very detailed reproduction of the reality in the simulation model. The disadvantage is the required effort to build up the simulation model. At the same time an optimization is not the goal of a DES-based approach. Therefore the integration of the simulation engine in a specific simulation software could be investigated. The activation of the different agility measures which are stored in a database could be automatized based on the stressing demand scenario. This would enable a mathematical optimization of the production network according to its agility. The optimized setup of a production network for an explicit demand scenario consists of specifically activated agility measures. This could be included in the increasing effort to digitize factories, discussed for example in Bracht et al. (2009).
The methodology to evaluate the agility is limited to the production network of a company. The part of the supply chain facing to the customer, for example distribution centers, was not included into the agility evaluation. Therefore the extension of the evaluation focus on the entire supply chain could be part of future research.
A further potential sophistication of the model engine could be the specification of the EBIT-model. Whereas the model developed in this thesis includes only a limited number of variable and fix costs, the integrated cost information can be specified. Potential extensions could be the inclusion of the inventory assessment or a detailed evaluation of the impact of investments.
The methodology evaluated the agility of the production network along three agility characteristics. For each of those an operational KPI was outlined as a result of the evaluation. Feedback from the partner company included the request for an agility evaluation by using an agility index. Whereas literature already provides qualitative agility indexes, see for example Lin et al. (2006) and Azevedo et al. (2012), a quantitative agility index is missing, especially an agility index which can be used by practitioners to assess and consequently also benchmark their own agility.

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A Appendix

Definitions	Characteristics					
	Speed	Flexibility	Profitability	Pro-activity	Customer-orientation	Innovation
Agility means a manufacturing system with extraordinary capabilities to meet the rapidly changing needs of the marketplace and a system that shifts quickly among product models and/or between product lines, ideally in real-time response to customer demand (Nagel et al. 1991).	x	x	-	x	x	-
The concept of Agile Manufacturing is built around the synthesis of enterprises with different core skills. These syntheses can be formed and changed very quickly, and provide agility, which brings a competitive advantage: being able to respond rapidly to market changes and to transfer knowledge and knowledge flow in dynamic teams, formed around clearly defined market opportunities, into new products and services (Kidd 1994).	x	-	-	-	x	-
Agility is dynamic, context-specific, aggressively change-embracing, and growth-oriented. It is not about improving efficiency, cutting costs, or battening down the business hatches to ride out fearsome competitive storms. It is about succeeding and about winning (Goldman et al. 1995).	-	-	x	x	-	-

AgileÂ manufacturing provides competitiveness.Â ManufacturingÂ processes based onÂ agileÂ manufacturingÂ are characterized by customer integrated process for designing,Â manufacturing, marketing, and support for all products and services; decision-making at functional knowledge points; stable unit costs; flexibleÂ manufacturing; easy access to integrated data; and modular production facilities. Agile manufacturing requires enriching of the customer; cooperating to enhance competitors, organizing to manage change and uncertainty, and leveraging people and information (Abair 1997).	-	x	-	-	x	-
Agile manufacturing is a new expression that is used to represent the ability of a producer of goods and services to thrive in the face of continuous change. These changes can occur in markets, in technologies, in business relationships and in all facets of the business enterprise (DeVor et al. 1997).	-	-	x	-	-	-

Agile manufacturing is driven by the need to quickly respond to the changing customer requirements. Agile manufacturing demands a manufacturing system to be able to produce efficiently a large variety of products and be reconfigurable to accommodate changes in the product mix and product designs. The manufacturing system reconfigurability and product variety are critical in agile manufacturing (Kusiak & He 1997).	x	x	x	-	-	-
Agile manufacturing is the ability to accomplish rapid changeover (minimum of change in tooling and software) between the manufacture of different assemblies utilizing essentially the same work-cell (Quinn et al. 1997).	x	x	-	-	-	-
Agile manufacturing is the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services (Gunasekaran 1998).	x	x	x	-	x	-

Agile manufacturing is a new paradigm that refers to the use of resources and people which can be changed quickly and cost-effectively, in unanticipated ways to cope with continuous and unanticipated change. Agile manufacturing enterprises are able to perform in such environment as effectively as mass production enterprises do in stable, repetitive environments (Shewchuk 1998).	x	x	x	-	-	-
Agility means using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place (Ben Naylor et al. 1999).	-	-	x	x	-	-
Agility in concept comprises responding to change (anticipated or unexpected) in proper ways and due time and exploiting changes and taking advantage of them as opportunities (Sharifi & Zhang 1999).	x	x	-	x	-	-
Agility for an organization is a paradox, in that an agile manufacturer has to be lean, flexible and able to respond rapidly to changing situations; yet it is recognized that no one company will have all the necessary resources to meet every opportunity (Sharp et al. 1999).	x	x	-	-	-	-

Agility is the ability to closely align enterprise systems to changing business needs in order to achieve competitive performance. Enterprises must be more flexible, responsive, and efficient to continuously evolve and adapt to their markets, be innovative and capture new markets (Vernadat 1999).	-	x	x	x	-	x
Agility is the successful exploration of competitive bases (speed, flexibility, innovation pro-activity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast changing market environment (Yusuf et al. 1999).	x	x	x	x	x	x
Manufacturing Agility is the ability to respond to and create new windows of opportunities in a turbulent market environment driven by individualizing customer requirements cost effectively, rapidly and continuously. Agile Manufacturing sets out to identify and apply practical tools, methodologies, and best practices that enable companies to achieve manufacturing agility within a turbulent business environment (Christian et al. 2001).	x	x	x	x	-	-

Agility derives from the physical ability to act (response ability) and the intellectual ability to find appropriate things to act on (knowledge management). Agility is expressed as the ability to manage and apply knowledge effectively, so that an organization has the potential to thrive in a continuously changing and unpredictable business environment (Dove 2001).	-	x	x	x	-	x
Agility is the ability to thrive and prosper in an environment of constant and unpredictable change. Agility is not only to accommodate change, but also to relish the opportunities inherent within a turbulent environment. The agile manufacturing provides all means to enable succeeding in such environments, including customer prosperity, people and information, cooperation within and between firms, and fitting a company for change (Maskell 2001).	-	-	x	x	-	x

Agility is characterized by cooperativeness and synergism (possibly resulting in virtual corporations), by a strategic vision that enables thriving in face of continuous and unpredictable change, by the responsive creation and delivery of customer-valued, high quality and mass customized goods/services, by nimble organization structures of a knowledgeable and empowered workforce, and facilitated by an information infrastructure that links constituent partners in a unified network (Sanchez & Nagi 2001).	-	x	x	-	x	-
Agility is the ability to thrive in an environment of continuous and often unanticipated change (Sarkis 2001).	-	-	x	-	-	-
Agility is the ability of an enterprise to operate profitably in a rapidly changing and continuously fragmenting global market environment by producing high-quality, high-performance, customer-configured goods and services (Tsourveloudis & Valavanis 2002).	-	-	x	-	x	-
An agile company can excel simultaneously on a wide range of competitive objectives including cost, quality, dependability, speed, flexibility and leading-edge technology products (Yusuf & Adeleye 2002).	x	x	x	-	-	-

Agile manufacturing includes the ability to respond quickly and effectively to current market demands, as well as being proactive in developing future market opportunities (Brown & Bessant 2003).	x	x	x	x	-	-
Real Agile Manufacturing (RAM) is the strategic process of responding to the competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets. RAM takes multiple-winners as an objective, integration as the means, with IT as an essential condition and core competence as the key (Jin-Hai et al. 2003).	x	x	x	-	-	-
In an agile supply chain the conduct of internal operations will be transparent to suppliers and customers, local teams of employees think globally and take virtual initiatives with teams in other companies. Responsiveness to changing competitive requirements becomes easier to master as a matter of routine, and with little penalties in time, cost and quality (Yusuf et al. 2004).	x	-	x	x	x	-
Agile Manufacturing is an emerging manufacturing paradigm, which considers agility a key concept necessary to survive against competitors under an unexpectedly turbulent and changing environment (Dowlatshahi & Cao 2006).	-	-	-	-	-	-

The agile enterprise is the latest stage of evolution of the idea of the organization or enterprise able to adjust to changes, comprising all concepts and propositions developed in the frame of research on the adaptive and flexible organization and manufacturing. A great influence is caused by a proactive, adaptive and resilient workforce (Sherehiy et al. 2007).	-	x	-	x	-	x
Agility is a manufacturing strategy that aims to provide manufacturing enterprises with competitive capabilities to prosper from dynamic and continuous changes in the business environment, reactively or proactively (Zhang & Sharifi 2007).	-	x	x	x	-	-
Agile manufacturing can be defined as an enterprise level manufacturing strategy of introducing new products into rapidly changing markets and the ability of an organization to thrive in a competitive environment characterized by continuous and sometimes unforeseen change (Andreeva 2008).	-	-	x	-	-	x

Organizational agility is adaption plus speed. Agile organizations excel across different kinds of activities: driving the long-term core business but also having the ability to shift focus and execute quickly to respond rapidly to short-term urgencies - or, even better, anticipate them so as to seize opportunities to be first to market and pull ahead of competitors (Cheese et al. 2009).	x	x	-	x	-	-
Agility is the capacity for moving quickly, flexibly and decisively in anticipating, initiating and taking advantage of opportunities and avoiding any negative consequences of change (McCann et al. 2009).	x	x	-	x	-	-
Organizational agility is the capacity to identify and capture opportunities more quickly than rivals do, which leads to higher revenues, higher customer satisfaction, improved efficiency and faster time-to-market (Sull 2009).	x	-	x	x	x	-
Agile manufacturing is a program would encompass exhaustively the technological and managerial elements for facilitating quick response to the customers' dynamic demands (Vinodh et al. 2010).	x	x	-	-	x	-
Being agile implies an increased ability to rapidly respond to changes in customer demand. Superior responsiveness is the key to competitive advantage (Inman et al. 2011).	x	-	-	x	-	-

Agility is to identify successfully the principles of competition (speed, flexibility, innovation, quality, profitability), integration of resources, and appropriate actions in the environment of knowledge with rapid changes, by providing customer-friendly products and services (Izadpanah & Yaghoubipoor 2012).	x	x	x	-	x	x
Agility is a cultivated dynamic capability that enables an organization to respond in a timely, effective, and sustainable way when changing circumstances require it; the potential to sense opportunities and threats, solve problems, and change the firm's resource base (Williams et al. 2013).	x	x	x	x	-	-