Identifying and Conceptualizing Methods for Mastering Complexity – A Complexity Drivers-Based Approach

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The President:

Prof. Dr. Bernhard Ehrenzeller

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LIST OF ABBREVIATIONS

AC	Automotive Company
AI	Automotive, Incorporation
BA	Building Automation
BOM	Bill of Materials
CTO	Chief Technology Officer
DFV	Design for Variety
DSM	Design Structure Matrix
et al.	et alii
FC	Forming Company
FMS	Flexible Manufacturing Systems
FTE	Full Time Employee
HSG	University of St. Gallen
ITEM	Institute for Technology Management, St. Gallen
MRQ	Main Research Question
MPS	Modular Product Structure
MTC	Medical Technology Company
PC	Pharmaceutical Company
QFD	Quality Function Deployment
RMS	Reconfigurable Manufacturing Systems
SRQ	Sub-Research Questions
STS	Socio-Technical Systems
TSM	Technology Super Market
VM	Variant Management
VMEA	Variant Mode and Effect Analysis

KURZZUSAMMENFASSUNG

Die stetig steigende Komplexität stellt eine Herausforderung für produzierende Unternehmen dar. Die Treiber dieser Komplexität sind vielfältig und beeinflussen das gesamte Unternehmen. Aktuelle Lösungen zur Beherrschung von Komplexität sind zahlreich; die Methoden fokussieren sich auf die Beherrschung von Markt-, Produkt- und Prozesskomplexität. Viele Unternehmen haben Schwierigkeiten die geeigneten Methoden zu identifizieren, um diese Komplexität zu beherrschen. In der Literatur werden Methoden als allgemein anwendbar beschrieben. In neueren Publikationen wird diese allgemeine Anwendbarkeit hinterfragt und die Notwendigkeit der Ableitung von Methoden auf Basis der spezifischen Herausforderungen des einzelnen Unternehmens in den Vordergrund gestellt. Publizierte Ansätze vernachlässigen jedoch die integrale Perspektive auf das Gesamtunternehmen zur Identifikation von Methoden zur Beherrschung von Komplexität.

Diese Arbeit befasst sich mit den in der Literatur identifizierten Defiziten und analysiert Einflussfaktoren in produzierenden Unternehmen, die bei der Identifikation und Konzeptualisierung von Methoden zur Beherrschung von Komplexität eine Rolle spielen.

Die vorliegende Arbeit gliedert sich in einen theoretischen, quantitativen, empirischen und konzeptionellen Teil. Anfangs werden Methoden zur Beherrschung von Komplexität aus der Forschung und Praxis klassifiziert, bewertet und selektiert. Die Abhängigkeit dieser Methoden mit Komplexitätstreibern wird im Rahmen einer wissenschaftlichen Studie und fünf Fallstudien in der produzierenden Industrie untersucht. Auf Basis von diesen fünf Fallstudien, werden ebenfalls Einflussfaktoren bei der Identifikation und Konzeptualisierung von Methoden zur Beherrschung von Komplexität explorativ erforscht.

Das Ziel dieser Arbeit ist die Entwicklung eines Prozessmodells zur Unterstützung von produzierenden Unternehmen bei der Identifikation und Konzeptualisierung von Methoden zur Beherrschung von Komplexität. Dazu werden die Kontingenz- und die Soziotechnische-Systeme-Theorie verwendet.

SUMMARY

Constantly increasing complexity represents a challenge for manufacturing companies. The drivers of this complexity are manifold and influence the entire company. Current solutions for mastering complexity are numerous; the methods focus mainly on mastering market, product, and process complexity. Many companies have difficulties in identifying suitable methods to control this complexity. In the specialist literature on this topic, methods are described as generally applicable. In more recent publications, this general applicability has been questioned, and the necessity of deriving methods based on the specific challenges of the individual company is emphasized. Current approaches, however, neglect an integral perspective on the enterprise to identify methods for mastering complexity.

The research in this dissertation deals with the deficits identified in the literature and analyzes influencing factors in manufacturing companies for identifying and conceptualizing methods for mastering complexity.

The dissertation is divided into theoretical, quantitative, empirical, and conceptual sections. Methods for mastering complexity from research and practice are classified, evaluated, and selected. The relationship of these methods to complexity drivers in the manufacturing industry is investigated in a quantitative study and includes five case studies in the manufacturing industry. Based on these five case studies from the manufacturing industry, influencing factors for identifying and conceptualizing methods for mastering complexity are explored and identified.

This dissertation aims to develop a process model to support manufacturing companies in identifying and conceptualizing methods for mastering complexity. To achieve this aim, it takes the perspective of the contingency and socio-technical systems theory.

1 Introduction

This initial chapter introduces the research project topic. In subchapter 1.1, the research background and motivation for the topic are described. Subchapter 1.2 focuses on the research objectives and the research questions of the dissertation. The theoretical background lies in the field of the contingency and socio-technical systems theory, which is described in subchapter 1.3. The research framework, described in subchapter 1.4, connects the individual elements of this dissertation and couples its connection to the research questions. The research methodology is described in subchapter 1.5, before the structure of the dissertation is outlined in subchapter 1.6.

1.1 Research background and motivation

Today, manufacturing companies are facing high complexity in their organization structures; this will increase due to different trends in the future (W. ElMaraghy et al., 2012). These trends encompass technological innovations, dynamic environmental conditions, changing customer requirements, market globalization, and market uncertainty (Feldhusen & Gebhardt, 2008, pp. 14–15; Perona & Miragliotta, 2004, p. 103; Theuer & Lass, 2016, p. 41). Today's markets are much more volatile in their demands and technologies compared to the markets in 1909, when Ford began his mass-production procedures and was able to earn high profits with just a single car model (Chakravarty & Balakrishnan, 2001, p. 587; Mourtzis & Doukas, 2014, p. 1). Nowadays, car companies, and many other manufacturing companies, offer wide-ranging product portfolios to meet individualized customer demands (Landherr & Westkämper, 2014, pp. 263–264).

The management of complexity, induced through individual customer demand, is regarded as the core challenge by many manufacturing companies (Amann et al., 2010, p. 4). As a reaction, manufacturing companies expand their product portfolios to build up a competitive advantage (Adam & Johannwille, 1998, pp. 6–7). This great variety of products creates complexity along the entire company value chain – in product development, production, and supply chain, as well as organizational processes (Miragliotta et al., 2002, p. 386; Wildemann & Voigt, 2011, p. 30). As a result, the efforts invested in product reviews and internal processes increase (Heina, 1999, pp. 35–36; Wildemann & Voigt, 2011, p. 29).

The understanding of the term complexity management in this dissertation builds upon the definition by Kirchhof (2003). This dissertation understands complexity management as the overall approach of developing, designing, and steering the variety and dynamic of a company and its environment (Kirchhof, 2003, p. 68).

Some sources distinguish the concept of complexity management in methods regarding the three complexity strategies of reduction, avoidance, and mastering of complexity (Bliss, 2000, p. 18; Wildemann, 2014).

Gabath (2010, p. 106) regards methods to stop the increase of complexity as belonging to the strategy of avoiding complexity. Methods for reducing complexity focus on decreasing the complexity which was built up in the past (Bliss, 2000, p. 18; Wildemann, 2014).

Based on the views of Malik (2013, p. 55) this dissertation regards complexity as an important "natural resource" in a fast-changing world. Therefore, companies need to emphasize their efforts on circumventing this complexity and reacting with suitable measures. In this dissertation, these measures are in focus and referred to as *methods for mastering complexity.*

In subject-specific literature, there are frequent discussions on the topic of complexity in various fields of research, including physics, biology, economics, chemistry, mathematics, computer science, engineering, and management, as well as philosophy (Bozarth et al., 2009; Simon, 1962, p. 467). As a result, the term complexity has a wide range of different definitions, and a widely accepted definition has not yet been formulated (Serdar-Asan, 2009, p. 9). In the online version of the Cambridge Dictionary (2020), the term "complexity" is defined as "the state of having many parts and being difficult to understand or find an answer to."

In the last decade, the relevance of factors which cause complexity – the so-called complexity drivers – has steadily gained significance among researchers and practitioners (Vogel & Lasch, 2016, p. 8). The online version of the Business Dictionary (2020) defines a driver as a cause of a condition of elements or a whole system. According to Meyer (2007, p. 26), a complexity driver increases the level of complexity in contrast to an initial situation. Several authors agree with the statement that managers need to understand their complexity drivers for mastering complexity (Heydari & Dalili, 2012, p. 64; Serdar-Asan, 2013, p. 534; Vogel & Lasch, 2016, p. 13).

Many companies face individual sets of complexity drivers, which increases the complexity not only in the product portfolio but also in the company's structures and processes (Jagersma, 2008, p. 239; Wildemann & Voigt, 2011, p. 30). A study conducted by the Division of Production Management, of the Institute of Technology Management at the University of St. Gallen (ITEM-HSG), indicated that the *volatility of customer demand* as well as the *variety of customer requirements* are the main reasons for high complexity in the manufacturing industry (Kohr et al., 2017, p. 55). In order to lower the effects of the complexity drivers on the costs along the entire value chain and inertia to react to changing customer requirements, a company's methods for mastering complexity need to suit the individual drivers (Amann et al., 2010, p. 121; Kohler, 2008, p. 159).

Hence, many methods for mastering complexity have been established to address the origins of complexity and allow manufacturing companies to achieve different targets (Maurer, 2017, p. 3). But not every method can be applied by every company. For example, applying the concept of modularity to product or production structures allows the company to split up the elements and assign them to modules to handle product and process variants more efficiently (Baldwin & Clark, 2004, p. 1). However, Baldwin and Clark (2006, pp. 199–200) also state that the efforts and the cost of modularizing depend on the product itself, and in some cases can be an offset compared to the value of modularity. Therefore, before implementing methods for mastering complexity, manufacturing companies should analyze their requirements and needs.

In topic-specific literature, these requirements and needs are described as contingencies influencing the management of manufacturing companies and the effectiveness of methods (Ketokivi & Schroeder, 2004; Sousa & Voss, 2008). Several studies urge support for interdependency between management practices and four contingencies: national context and culture (Ebrahimpour & Cullen, 1993; Voss & Blackmon, 1998), strategic context (Hobbs, O. Kermitt, Jr., 1994; Sila, 2007), firm size (Cagliano et al., 2001; Shah & Ward, 2003), and organizational context variables (Ahmad & Schroeder, 2003; Shah & Ward, 2003). Managers need to analyze the individual complexity drivers, and the contingency factors, to choose the methods for managing them (Kohler, 2008, p. 159; Sousa & Voss, 2008; Vogel & Lasch, 2016, p. 12).

Nevertheless, topical literature lacks research findings regarding influencing factors within manufacturing companies for identifying and conceptualizing methods for mastering complexity (Sousa & Voss, 2008; Wildemann & Voigt, 2011, pp. 162–163).

This present research project aims to contribute to the understanding of these factors and their roles, building upon the theoretical background of the contingency and the socio-technical systems theory. One focus lies on the dependency of methods for mastering complexity on contingency factors and complexity drivers. As a result, a process model is suggested which supports managers in identifying and conceptualizing methods for mastering complexity.

1.2 Research objectives and research questions

This chapter describes the design of the research project. As a reaction to increasing complexity in the manufacturing industry, the interest of scholars and practitioners in methods along the value chain has grown. Due to a multitude of factors influencing manufacturing companies, managers face challenges in identifying and conceptualizing methods for mastering their complexity. This present research project aims at answering the following main research question (MRQ).

MRQ: *How can manufacturing companies be supported in mastering their complexity?*

The author formulates five sub-research questions (SRQ) to assist in answering the main research question.

SRQ 1: *What are complexity drivers along the value chain in the manufacturing industry?*

SRQ 2: *What is the underlying structure of the complexity drivers?*

SRQ 3: *What methods exist for mastering complexity along the value chain in the manufacturing industry?*

SRQ 4: *What are the influencing factors for identifying and conceptualizing methods for mastering complexity in the manufacturing industry?*

SRQ 4.1: *What is the relationship between methods for mastering complexity and complexity drivers in the manufacturing industry?*

SRQ 4.2: *How do other factors influence manufacturing companies in identifying and conceptualizing methods for mastering complexity?*

SRQ 5: *How can a process model for identifying and conceptualizing methods for mastering complexity be designed?*

To help fill in the research gap, the primary purpose of this research project is to support companies in identifying and conceptualizing methods for mastering their complexity. The project aims to identify the relevant complexity drivers along the value chain in the manufacturing industry by investigating the underlying structures, in order to answer sub-research questions 1 and 2 (SRQs 1 & 2). Sub-research question 3 (SRQ 3) is dedicated to the methods for mastering complexity in the manufacturing industry. Based on quantitative data and case study research, a structured analysis of the relationship between the complexity drivers and the methods for mastering complexity was conducted. Furthermore, using a qualitative, explorative approach in Chapter 4, further influencing factors for identifying and conceptualizing methods for mastering complexity were analyzed. In sum, these results help to answer sub-research question 4 (SRQ 4). The findings of the sub-research questions 1 – 4 are incorporated in order to derive a process model to support managers in identifying and conceptualizing methods suitable for the complexity and the characteristics of their organization. The model answers sub-research question 5 (SRQ 5).

1.3 Theoretical background

This subchapter describes the two theoretical "lenses" – contingency and socio-technical systems theory – chosen in this research project.

1.3.1 Contingency theory

In this project, the contingency theory was chosen as the theoretical "lens" for viewing the decision-making process of manufacturing companies in choosing methods for mastering complexity along the value chain. This theory casts doubts about the existence and practical relevance of organizational principles with universal validity. As one of the earliest researchers, Woodward (1980) required considering the individual setting of an organization in a decision-making process. As every organization is confronted with different contingency variables, managing them is different from company to company. The contingency theory claims that there is no best way to organize a company (Lawrence & Lorsch, 1976).

The concept of *fit* is an integral element of the contingency theory and has its roots in the organization theory and the literature regarding strategic management (Ginsberg & Venkatraman, 1985, p. 422). Concerning the organization theory literature, *fit* mainly describes relationships between structure and environment, whereas the strategic management literature emphasizes the relationship between strategy and environment (Pfeffer, 1984). Furthermore, Zajac et al. (2000) distinguish between the two literature streams regarding the ambiguity and multidimensionality in making recommendations to organizational adaptations based on environmental factors. Accordingly, the organization theory regards *fit* as rather unambiguous and unidimensional, and permits deriving an explicit recommendation concerning specific environmental factors (Zajac et al., 2000, p. 431). In contrast, strategic management literature regards the concept of *fit* as ambiguous and multidimensional, which results in challenges in proposing clear recommendations (Zajac et al., 2000, p. 430).

In the specific literature, two dimensions of *fit* are distinguished – 1) *conceptualization of fit* and 2) *domain of fit* (Venkatraman & Camillus, 1984, pp. 514–515). The dimension *conceptualization of fit* aims at describing the *content of fit* – **what** should be done – or the *process of fit* - **how** it is to be developed (Venkatraman & Camillus, 1984, p. 514). Concerned with identifying the source of the factors that are analyzed, the fit domain comprises three categories – internal, external, and integrated (Venkatraman & Camillus, 1984, p. 515). The external perspective aims at describing the *fit* between environmental factors and strategy, while the internal lens focuses on the relationship between organizational structure and strategy. A more holistic view is provided by the integrated perspective – which includes environmental, strategic, and organizational elements (Venkatraman & Camillus, 1984, p. 515).

This present research project has examined the two dimensions as follows: The dimension domain of *fit* takes an integrated view as it investigates the *fit* of complexity drivers and characteristics internal to the process of identifying and conceptualizing methods in manufacturing companies. Regarding the conceptualization of *fit*, the content of *fit* and the process of *fit* are analyzed. In SRQ 1 and SRQ 2, the author identifies the relevant complexity drivers and analyzes their underlying structure. SRQ 3 analyzes the implementation degree of methods for mastering complexity.

Furthermore, quantitative and qualitative data are analyzed to find out whether there is a relationship between applied methods and the complexity drivers (SRQ 4.1). Additionally, in an exploratory case study research, influencing factors for identifying

and conceptualizing methods are analyzed (SRQ 4.2). Hence the first four sub-research questions investigate the content of *fit*. The observations of these questions are integrated into the development of a process model to support managers in identifying and conceptualizing methods for mastering complexity (SRQ 5). Hence, the process model aims at investigating the process of *fit*.

1.3.2 Socio-Technical Systems theory

The socio-technical systems (STS) theory has been additionally chosen to investigate influencing factors for identifying and conceptualizing methods for mastering complexity in the manufacturing industry.

The STS theory regards organizations as the combination of social systems (employees, their needs and relationships) and the technical systems (technologies, machines, workstations, processes) of a company. Applying socio-technical approaches to system design reduces the risk of not achieving the desired contribution of the systems to the organization's goals (Baxter & Sommerville, 2011, p. 4). According to Cherns (1976, p. 784), the joint optimization of technical and social aspects support an organization in achieving its targets.

To ensure the consideration of socio-technical aspects when designing organizations, Cherns (1976, 1987) formulated ten principles. In 1976 he proposed his principles, and then modified them in 1987, taking into consideration "the needs of the organization as a society" (Cherns, 1987, p. 153). To account for new information technologies and a range of modern management practices and working habits Clegg extended the earlier formulations (Clegg, 2000, p. 463). He classified 19 principles into the meta, content, and process levels (Clegg, 2000, p. 465). Clegg's (2000) principles (1, 2, 3, 10, 12, 16) are also listed by Cherns (1987).

Cherns (1976, 1987) and Clegg (2000) derived several principles for achieving synergy between a company's technical and social systems. This present dissertation applies these principles to mastering complexity in the manufacturing industry. Organizations that can mitigate the negative effects of complexity, while at the same time mastering its positive ones, can cope with continuous change, as well as increasing complexity (W. ElMaraghy et al., 2012, p. 793; Keckl et al., 2016, p. 334). Managing socio-technical systems is crucial to reap the benefits of high complexity (W. ElMaraghy et al., 2012, p. 793).

Therefore, in this research project, these principles are revisited in Chapter 5 to derive a process model for identifying and conceptualizing methods for mastering complexity along the value chain of manufacturing companies.

The 10 principles of Cherns (see Table 1 and Table 2) and the 19 principles of Clegg (Table 3, Table 4, and Table 5) are listed and described in the following tables (Cherns, 1987, pp. 154–160; Clegg, 2000, p. 463).

Table 1: Socio-technical systems principles by Cherns (1976, 1987)

No.	*Socio-technical systems principles*	*Source*	*Description*
1	***Compatibility***	Cherns (1976, 1987)	This principle emphasizes the relevance of the *fit* between applied means and the objective. Applied to the field of complexity management, it means that the methods applied by the company should fit the individual characteristics as well as the aspired to results.
2	***Minimal Critical Specification***	Cherns (1976, 1987)	Consisting of a negative and a positive aspect, this principle can be widely applied. The negative aspect claims that a specification should not exceed what is absolutely essential. The positive aspect sets the requirements for identifying what is essential. Accordingly, this implies "minimal critical specification of a task, the minimal critical allocation of tasks to jobs […] and the specification of objectives with the minimal critical specification of methods of obtaining them." (Cherns, 1987, p. 155)
3	***Variance control***	Cherns (1987)	This principle states the relevance of no variance being exported across "unit, departmental, or other organizational boundaries" for successful organizational design. This principle is closely related to the following Principles 4 and 5.
4	***Boundary location***	Cherns (1976, 1987)	This states that an organization should not draw boundaries in order to establish hurdles for information and knowledge sharing. Otherwise, it may result in a control and information loop and thus in delays of corrective actions, leading to endless conflicts.
5	***Information flow***	Cherns (1976, 1987)	This principle suggests avoiding interruption of information. As a result, the information is delivered to the right recipient at the right time. Obstacles for the information flow can be found on vertical as well as horizontal levels.
6	***Power and authority***	Cherns (1976, 1987)	This principle counsels that people should have access and the authority to command the resources they need to carry out their responsibilities. In return, they accept the responsibility for the resources' performance.

Table 2: Socio-technical systems principles by Cherns (1976, 1987) (continued)

No.	*Socio-technical systems principles*	*Source*	*Description*
7	***Multifunctional principle***	Cherns (1987)	Cherns (1987) distinguishes between mechanism and organism, for a company to adapt to its environments. Thus, it can either add new roles or modify old ones in order to establish the capabilities needed. The latter "enlarges the roles and the response repertoire of individuals and teams without complicating the lines of command." Adding new roles, on the other hand, leads to "confusion of authority." (Cherns, 1987, p. 158)
8	***Support congruence***	Cherns (1976, 1987)	This states that the support systems and its recipient should be congruent to each other. The design of these systems can either start with adapting existing systems or radically designing the ideal system for the recipients.
9	***Transitional organization***	Cherns (1987)	The period of transition from the old to the new organization needs planning and design – "the transitional organization is both different and more complex than either new or old." (Cherns, 1987, p. 159)
10	***Incompletion, or the Forth Bridge Principle***	Cherns (1976, 1987)	The myth of stability is essential to cope with demands of change, but it is well known that the period of transition leads to a period of another transition rather than a future stable state. "The stability myth is reassuring but dangerous if it leaves us unprepared to review and revise." (Cherns, 1987, pp. 159–160)

Table 3: Socio-technical systems principles by Clegg (2000)

No.	*Socio-technical systems principles*	*Source*	*Type of principle*	*Description*
1	***Design is systemic***	Clegg (2000)	Meta principle	This perspective is implicit in Cherns' principles and arguments.
2	***Values and mindsets are central to design***	Clegg (2000)	Meta principle	This is similar to the views presented by Cherns.
3	***Design involves making choices***	Clegg (2000)	Meta principle	The model includes multi-dimensional perspectives to evaluate identifying and conceptualizing methods for mastering complexity
4	***Design should reflect the needs of the business, its users, and their managers***	Clegg (2000)	Meta principle	A system needs to be useful, to meet some articulated purpose, to meet the needs of the business, its users, and their managers. Such pragmatic concerns may be based on current or future needs. (Clegg, 2000, p. 466)
5	***Design is an extended social process***	Clegg (2000)	Meta principle	This principle considers that design is extended over lengthy periods of time. Design continues beyond implementation and throughout use.
6	***Design is socially shaped***	Clegg (2000)	Meta principle	This principle argues that wider social factors help influence the sorts of design problem that are addressed, and the kinds of design solution that are attended to and invested in. Design is subject to social movements and trends. (Clegg, 2000, p. 467)
7	***Design is contingent***	Clegg (2000)	Meta principle	This idea was implicit in Cherns' writing.
8	***Core processes should be integrated***	Clegg (2000)	Content principle	Processes were not explicitly included in Cherns' principles, but this principle subsumes his ideas on boundary location, information flow, and power and authority.

Table 4: Socio-technical systems principles by Clegg (2000) (continued)

No.	*Socio-technical systems principles*	*Source*	*Type of principle*	*Description*
9	***Design entails multiple task allocations between and amongst humans and machines***	Clegg (2000)	Content principle	This principle includes Cherns' multifunctional principle and his criteria for job design, but extends to incorporate consideration of task allocation between humans and machines.
10	***System components should be congruent***	Clegg (2000)	Content principle	This is equivalent to Cherns' ideas on support congruence.
11	***Systems should be simple in design and make problems visible***	Clegg (2000)	Content principle	The proposition is that sociotechnical systems should be simple and that this will promote their ease of use. This principle applies to the detail of design (including, for example the design of human-computer interfaces and interactions), but also to the broad concept. (Clegg, 2000, p. 471)
12	***Problems should be controlled at source***	Clegg (2000)	Content principle	This is equivalent to Cherns' principle of variance control.
13	***The means of undertaking tasks should be flexibly specified***	Clegg (2000)	Content principle	This amends Cherns' ideas on minimal critical specification, in part to deal with the issue of technical design for complex systems.
14	***Design practice is itself a sociotechnical system***	Clegg (2000)	Process principle	This subsumes Cherns' principles of transitional organization and incompletion.

Table 5: Socio-technical systems principles by Clegg (2000) (continued)

No.	*Socio-technical systems principles*	*Source*	*Type of principle*	*Description*
15	***Systems and their design should be owned by their managers and users***	Clegg (2000)	Process principle	This amends Cherns' principle of compatibility and involves a change from his emphasis on user participation to user ownership.
16	***Evaluation is an essential aspect of design***	Clegg (2000)	Process principle	This is mentioned briefly under Cherns' principle of incompletion.
17	***Design involves multidisciplinary education***	Clegg (2000)	Process principle	The notion of multidisciplinarity is implicit in his ideas.
18	***Resources and support are required for design***	Clegg (2000)	Process principle	Organizations undertaking the design of new systems need to invest resources. Resources and support, here are taken to include a number of interrelated elements: money, time, and effort.
19	***System design involves political processes***	Clegg (2000)	Process principle	The above principles highlight the need to recognize the political nature of change. Design debates concerning values, choices, ownership, processes, task allocation, evaluation, and resources inevitably raise political issues in organizations. (Clegg, 2000, p. 474)

1.4 Research framework

The research framework in Figure 1 shows the research elements and their relationships to one another, as well as the research objective of this dissertation. The main elements of the framework are *complexity drivers, methods for mastering complexity, complexity along the value chain,* and *contingencies*. In the illustration, the elements are connected in various ways. The complexity along the value chain can be influenced by both the complexity drivers and the methods applied for mastering the complexity of an organization. Equally, the applied methods and the drivers can be related to one another. Contingencies can influence an organization's decision to apply methods for mastering the complexity along the value chain. Furthermore, the research framework includes the research questions of this dissertation and assigns them to the elements in question.

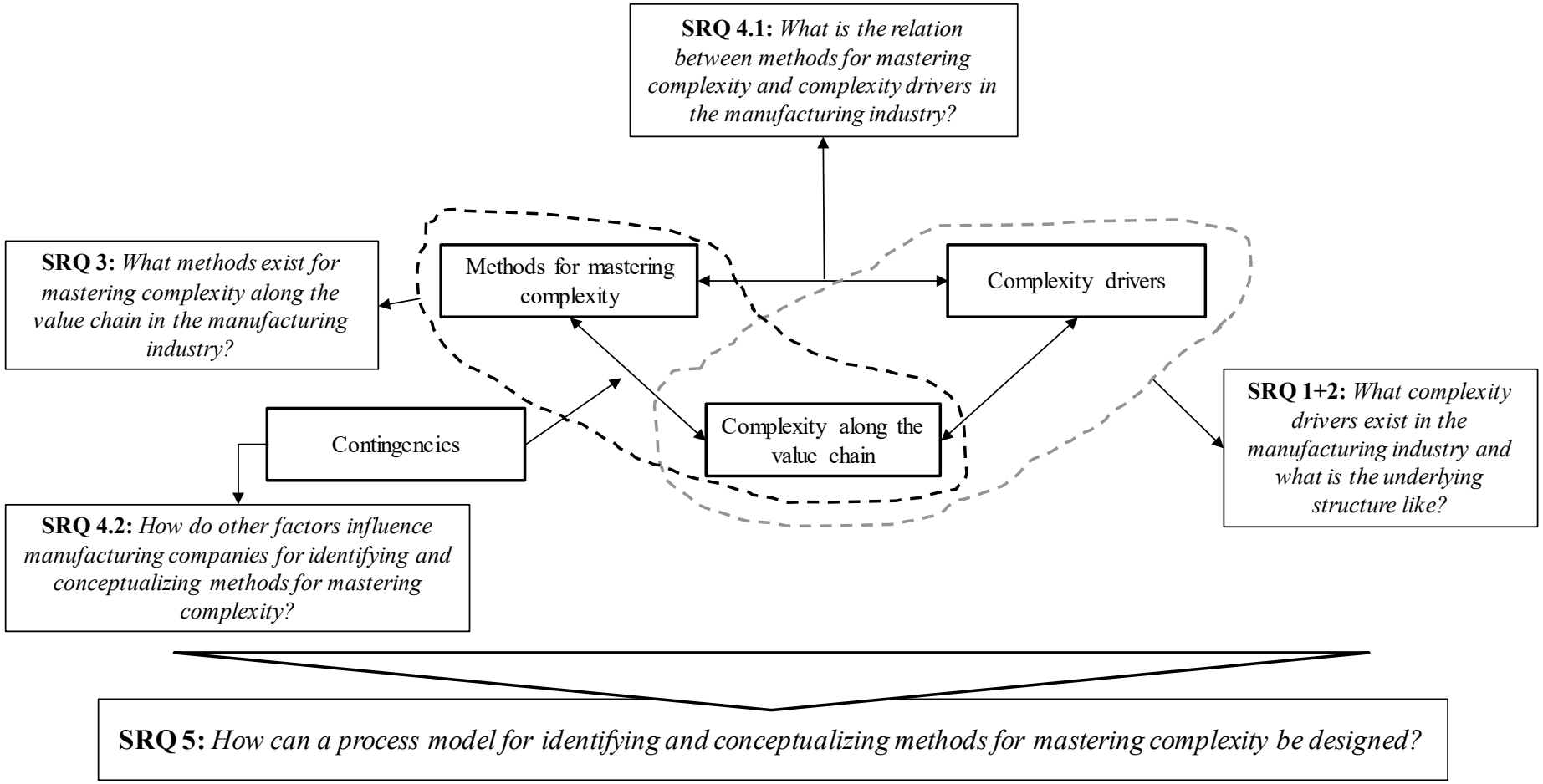


Figure 1: Research framework and research questions

1.5 Research methodology

This research project is based on an iterative research process as demonstrated in Figure 2. Kubicek (1977) described an iterative heuristic approach that starts with a research problem based on initial findings from literature and practice. His findings helped to build a conceptual research framework to describe the interrelationships and elements of the underlying problem (see Figure 1). Questions were derived from the preliminary theoretical knowledge and applied to practical situations, which led to the step of data collection, including practical problems and phenomena aiming at answering the research questions. Contributions to theoretical knowledge were gained through critical reflection and abstraction. This iterative process led to an accumulation of findings, which were transformed into theoretical knowledge. In this process, the research framework was tested and adapted through data collection and reflection.

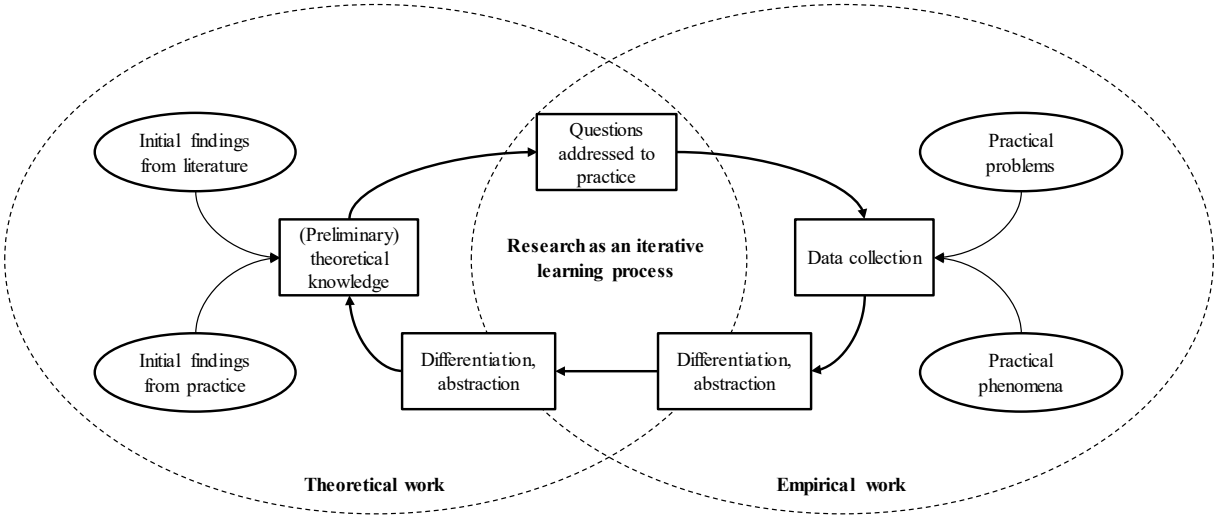


Figure 2: Research process (adapted from Kubicek, 1977, p. 14; Baumbach, 1998, p. 15 and Tomczak, 1992, p. 84)

Figure 2 illustrates the research steps of this project. First, based on interviews with industry experts from manufacturing companies and literature research, the practical relevance was identified, and the research problem defined. As a result, the research gap, the underlying questions, and the research framework were derived. The author identified complexity drivers and methods for mastering complexity of manufacturing companies based on extensive desk research. Second, based on quantitative and qualitative data from the manufacturing industry, the author investigated factors in the process of identifying and conceptualizing methods for mastering complexity. Based on a quantitative study and case study research, the relevance of complexity drivers and

methods for mastering complexity and its relationships was analyzed. Additionally, in case studies with manufacturing companies, the author analyzed further influencing factors for identifying and conceptualizing suitable methods for mastering the specific individual complexity. The results of the first four steps were combined in a conceptual design phase in order to derive a process model. The process model aims to support managers in identifying and conceptualizing methods for mastering complexity.

1.6 Structure of the dissertation

This dissertation consists of six chapters, including literature research, an empirical – quantitative and qualitative – section, a conceptual part, and a concluding wrap-up.

Introduction (Chapter 1)

This chapter describes the research background and the motivation for the dissertation, along with the research objectives and the underlying research questions. It also includes theoretical background information and elaborates on the research framework and the research methodology for answering the research questions.

State of research (Chapter 2)

The second chapter provides definitions in the field of complexity management, and identifies research gaps, based on two literature reviews. The first literature review was conducted to determine methods for mastering complexity. By applying a funnel model, the relevant methods for mastering complexity are identified and their relationship to complexity drivers based on literature are investigated. The second literature review focuses on determining publications in the field of identifying and conceptualizing methods for mastering complexity. Finally, the research gaps identified in both literature reviews are described.

Quantitative approach (Chapter 3)

Chapter 3 describes the quantitative study conducted by the research team. The chapter is structured into six subchapters, the first five of which describe the design and characteristics of the study, as well as the data analysis. In the last part, the results are described, with an analysis of the underlying structure of the complexity drivers and the

link between complexity drivers and methods for mastering complexity. The last subchapter presents a table visualizing the relationships based on the literature analysis and the results of the quantitative study.

Qualitative approach (Chapter 4)

Chapter 4 outlines the case study research. Initially, the chapter introduces the case study methodology and elaborates on the case selection, data collection, and the analytical process. The with-in analysis in Chapter 6 describes the individual findings of the five case companies. In the cross-case analysis, similarities and differences among the individual case companies are identified. An idealized table shows a comparison of the relationships between methods for mastering complexity and complexity drivers identified in the literature, the quantitative study, and the case studies.

Suggested model to support identifying and conceptualizing methods for mastering complexity (Chapter 5)

The fifth chapter aims at combining the insights from Chapters 3 and 4 to derive a process model for supporting manufacturing companies in identifying and conceptualizing methods for mastering complexity. It elaborates on the elements of the model and the related literature. Furthermore, the process model is applied to a company from the medical technology industry.

Summary and outlook (Chapter 6)

The sixth and last chapter sums up the results of the dissertation and its contribution to theory and practice in the field of complexity management. Furthermore, the limitations of the research and possible future research in this field are discussed.

2 State of research

This research project aims to develop a process model for identifying and conceptualizing methods for mastering complexity in the manufacturing industry. Chapter 2 provides the relevant background information on the topic of mastering complexity along the value chain in manufacturing companies. Subchapter 2.1 outlines the general definition of the value chain and its activities in manufacturing companies. Subchapter 2.2 describes the term "complexity", its relevance in managing organizations, and current trends and developments reflected in the literature. Subchapter 2.3 addresses the different methods manufacturing companies can apply to master complexity. Subchapter 2.4 describes previous work on complexity drivers. Subchapter 2.5 focuses on the procedure of conducting literature reviews. Subchapter 2.6 analyzes the body of knowledge on the topic of methods used for mastering complexity, describes the funnel model for identifying relevant methods for mastering complexity, and describes their relationships to complexity drivers. In subchapter 2.7 the body of knowledge related to the topic of identifying and conceptualizing methods for mastering complexity is described. After a summary, subchapter 2.8 formulates the research gaps.

2.1 The value chain

All firms perform various activities, including design, production, marketing, delivering, and maintenance to make their product(s) successful. These activities are carried out in a specific order, which can be described in the form of a value chain. The generic value chain is separated into support activities (firm infrastructure, HR, technology development, procurement) and primary activities (inbound logistics, operations, outbound logistics, marketing & sales, service). The diverse activities along the value chain are critical factors for a company in achieving a competitive advantage. The focus along the value chain differs among companies and industries. (Chang & Hwang, 2002, p. 127; Porter, 1998, pp. 36–37)

The term value refers to the number of customers willing to offer a firm's products. The elements a value chain consists of cannot be defined universally. Even companies in the same industry differ in the designs of their value chains – as this is one factor of competitive advantage.

Nevertheless, a definition of the activities of a value chain relating to manufacturing firms needs to be offered. It should encompass all functions which are confronted with complexity and can influence the impact of the complexity on the manufacturing company. Therefore, it should include functions like product design and development, marketing, production, procurement, inbound & outbound logistics, and service.

2.2 Definition and impact of complexity

In recent decades, the term “complex” has been used widely to describe various situations (Maurer, 2017, p. 17). Complexity is discussed in various fields of research, including physics, biology, economics, chemistry, mathematics, computer science, engineering, and management, as well as philosophy (Bozarth et al., 2009; Simon, 1962, p. 467). As a result, complexity has a wide range of different definitions, whereas a widely accepted definition has not yet been agreed upon (Serdar-Asan, 2009, p. 9).

The definitions of complexity in the field of engineering are diverse and serve specific fields of application (Lindemann et al., 2009). The online version of the Cambridge Dictionary defines the term “complexity” as “the state of having many parts and being difficult to understand or find an answer to” (Cambridge Dictionary, 2020). Complex systems are usually described as being composed of highly interconnected factors, preventing the separate alteration of one factor without evoking changes in others (Ashby, 1956). Nevertheless, to master the influence of complexity its origins, importance, and impact need to be understood (Heydari & Dalili, 2012, p. 64; Serdar-Asan, 2013, p. 534).

In an engineering context, the total concept of complexity encompasses market complexity, product complexity, organizational complexity, and process complexity. In these fields, complexity is directly related to the number of elements in the system and their degree of dependencies. As a result, the system may become non-transparent for the people involved. (Maurer, 2017, p. 20)

Motivated by developments towards buyer markets, manufacturing companies are increasingly confronted with higher fragmentations of their customer markets, as well as increases in dynamics and intensity of competition (Bliss, 2000, p. 8). As a result, companies need to emphasize diversification and differentiation strategies and offer a broader product portfolio. In consideration of the fact that incremental expansion of the product portfolio only leads to marginal higher costs, the negative impact of these

decisions on the company's process in the long term is not foreseeable. Adam and Johannwille (1998, p. 7) describe this phenomenon as the "complexity trap", which leads to a higher complexity along the entire value chain of the company.

A company cannot measure the impact of variant-induced complexity on the costs along the value chain with traditional accounting systems. Allocating the costs based on quantity or value dependency leads to cross-subsidization of newly introduced products by the already existing product portfolio. (Robin Cooper & Kaplan, 1988, p. 20; R. L. Cooper & Kaplan, 1988, p. 97; Johnson & Kaplan, 1987, p. 22)

Hence, a growing product portfolio is the result of the company's response to its external complexity. As a first step, it leads to an increasing product complexity, which in turn leads to a higher level of process complexity. (Schuh, 1989, p. 8)

Nevertheless, this induced complexity also has positive effects. Through diversification, variety, and differentiation, various market needs can be served (Picot & Freudenberg, 1998, p. 69). The variety theory of Ashby (1956) states that every system's success is dependent on the number of offered compensation alternatives that are potentially available for different environmental states. Hence, the complexity of a company has beneficial and harmful implications, which leads to a central dilemma – on the one hand, the company aims at lower costs for production and internal processes; and on the other hand, it seeks higher market shares and revenue.

Recent publications in this area discuss the relevance of complex adaptive systems (CAS) for the management of organizations (Aelker et al., 2013; Akgün et al., 2014; Bohórquez Arévalo & Espinosa, 2015). CAS is related to the field of studying systems with interrelated elements. Therefore, the systems' global behavior is more dependent on the interrelation of its elements than on the behavior of each element (Holland, 1992, p. 20).

Lichtenstein et al. (2006) describe the change of leadership within CAS. In complex adaptive systems, relationships are rather defined by interactions between "heterogeneous agents and across agent networks" than by hierarchy. CAS consist of agents, groups of individuals, who positively interact with each other based on their interests, goals, and sharing of worldviews. As a response to external and internal pressures tensions develop between the agents, creating learning effects in the sense of capabilities and innovation within the CAS. (Lichtenstein et al., 2006, p. 3)

Complexity within manufacturing companies affects the entire value chain and requires an integrated perspective to master it efficiently. Methods for mastering complexity need to incorporate the interdependency of the complex adaptive systems. As a result, the negative effects of complexity can be reduced while maintaining the positive effects.

2.3 Methods for mastering complexity

The complexity within companies and the identification of a suitable degree of complexity gave rise to various management principles in the 1990s (Reiß, 1993, p. 54). According to Bliss (2000, p. 15), the development of complexity management proceeded in three phases. In the beginning, methods for mastering complexity were mainly applied in the manufacturing sector to handle a wide variety of products more efficiently (Bliss, 2000, p. 16). In this phase applying flexible and highly automated value chains aimed at facilitating the production of a perfectly customized product portfolio (Adam, 1992, p. 10). An evaluation regarding costs and cycle time pointed towards serious inefficiencies and therefore demanded an adapted approach. In the second phase, additional stand-alone methods of e.g. lean management, business reengineering, and variant management were implemented (Bliss, 2000, p. 16).

Complexity affects the entire supply chain of an organization. Therefore individual, isolated approaches for mastering complexity are regarded as ineffective. It requires an integrative approach, which is represented in the third phase of the development of complexity management (Gießmann, 2010, p. 49). As a reaction to increasing individual customer demands, companies must implement methods for complexity management in order to stay efficient and competitive.

In the literature, various methods used along the value chain have been described (Heina, 1999; C. M. Meyer, 2007; Wildemann, 2014; Wildemann & Voigt, 2011). This present dissertation includes a literature review of highly relevant sources, conducted to identify the methods for mastering complexity in the manufacturing industry. The results and the funnel model for selecting the relevant methods for mastering complexity are described in subchapter 2.6.

2.4 Complexity drivers

As complexity drivers can cause an increase in variety, dynamism, and volatility (Blecker et al., 2005; C. M. Meyer, 2007), mastering complexity within companies

needs to identify and control the critical complexity drivers (Maurer, 2017; Schuh, 2005; Vogel & Lasch, 2016).

In today's literature, there is no common understanding of the term "complexity driver" (Buob, 2010; C. M. Meyer, 2007).

In general, however, a driver is described as:

- A condition or decision that causes subsequent conditions or decisions to occur as a consequence of its occurrence.
- An element of a system that has a major or critical effect on the associated elements or the entire system.
- A root cause of a condition or measurement. (Business Dictionary, 2020)

As a general definition of the term *complexity drivers*, Vogel and Lasch (2016, p. 18) offer the following: *"Complexity drivers are factors, which influence a system's complexity and company's target achievement. They are responsible for increasing system's complexity level and help to define the characteristics or the phenomenon of a system's complexity."*

Various complexity drivers in organizations have been described in specialized publications; the authors focus mainly on specific areas along the value chain of companies in specific industries.

C. M. Meyer (2007) distinguishes between two categories 1) general complexity drivers and their influences on a company, and 2) major complexity drivers and their influences regarding logistics. He describes 127 complexity drivers and clusters them into fourteen categories (C. M. Meyer, 2007).

Serdar-Asan (2009, 2011, 2013) describes complexity drivers in the supply chain, whereas other parts along the value chain are left vaguely outlined. In her first paper, she identifies complexity drivers and their categories of origin, offering solution strategies for complexity driver handling.

Wildemann and Voigt (2011) distinguish internal and external complexity drivers in manufacturing companies, to quantify product portfolio, process, and structure complexity. They outline 115 different complexity drivers, based on literature research and case studies, and cluster them into nine driver categories. In a final step, the complexity drivers are condensed into ten external and twenty internal complexity

drivers, in order to easily handle them. The drivers' relevance and influences on the company processes were investigated based on an online survey.

As a result of a literature review, Vogel and Lasch (2016, p. 24) derive a list of 480 complexity drivers from 223 literature sources related to complexity drivers in manufacturing and along the value chain. For a better understanding and overview, Schoettl et al. (2014) suggest that the list be condensed into a small, abstract, and well-defined collection. Therefore, a clustering of the complexity drivers into categories is recommended.

Table 6: Overview of complexity driver clusters and their occurrence in literature (adapted from Vogel and Lasch (2016, p. 30))

		Value Chain									
Clusters of complexity drivers	*Number of specific complexity drivers*	*General in manufacturing companies*	*Product development*	*Procurement/purchasing*	*Logistics*	*Production*	*Order processing/distribution/sale*	*Internal supply chain*	*Remanufacturing*	*General in value chain*	*Total literature occurrence in all fields*
External complexity											
Social complexity	25	56	6	1	12	6	10	9	0	1	101
General market-related complexity	18	53	5	2	10	5	7	9	0	4	95
Demand complexity	7	59	3	2	12	6	7	15	4	4	112
Competitive complexity	9	35	5	0	6	2	6	5	4	0	63
Supply complexity	19	31	0	3	9	4	4	11	3	0	65
Technological complexity (external)	9	26	4	0	3	1	2	3	0	1	40
Internal correlated complexity											
Target complexity	7	12	3	1	4	0	1	0	0	0	21
Customer complexity	10	50	1	1	7	2	8	8	2	0	79
Product and product portfolio complexity	43	133	18	6	21	26	14	27	8	6	259
Technological complexity (internal)	15	15	7	1	4	2	1	2	3	0	35
Product development complexity	8	8	4	0	0	4	1	0	0	1	18
Supply process complexity	7	3	0	1	1	1	1	2	0	0	9
Service complexity	3	4	0	1	0	0	1	0	0	0	6
Remanufacturing complexity	2	5	0	0	0	0	0	0	0	0	5
Internal autonomous complexity											
Organizational complexity	105	142	17	7	22	27	32	29	6	2	284
Process complexity	25	39	7	3	7	14	6	9	0	1	86
Production complexity	39	39	4	2	8	19	3	11	1	0	87
Planning, control and information complexity	41	38	4	0	10	6	7	7	0	0	72
Resource complexity	9	8	1	0	1	1	1	1	0	0	13
Logistics complexity	17	2	1	1	5	5	3	9	0	0	26
Sales and distribution complexity	40	18	3	0	3	1	9	4	0	2	40
General complexity	28	48	1	4	2	8	0	7	1	1	72
Total amount of complexity driver literature occurence	486	824	94	36	147	140	124	168	32	23	

Clusters of complexity drivers

Complexity drivers can be distinguished as external or internal. Whereas actions of the company can actively influence internal complexity drivers, external complexity drivers are not created by the company, hence their negative impacts on the internal processes of a company need to be mastered. External complexity results in a higher complexity inside of the company and is therefore closely linked to the internal complexity drivers. (Vogel & Lasch, 2016, p. 27; Wildemann & Voigt, 2011, p. 53)

The categories of internal and external complexity are specified in the specialized literature. External complexity consists of *society complexity* and *market complexity* (Gießmann, 2010; Keuper, 2004; Lasch & Giessmann, 2008; Marti, 2007)

Society complexity embraces cultural, ecological, legal, and political factors, as well as standards and regulations (Vogel & Lasch, 2016, p. 28). *Market complexity* consists of the clusters *demand, competitive,* and *supply complexity* (Keuper, 2004; Lasch & Giessmann, 2008)[1] and *technological complexity* (Bliss, 2000; Marti, 2007)[2]. Furthermore, there are several single complexity drivers unassignable to the categories above; Vogel and Lasch (2016) cluster these drivers within general market-related complexity.

The category of *internal complexity* can be separated into *internally correlated complexity* and *autonomous complexity*. According to the literature, the *correlated complexity* can be subdivided into *customer complexity*, *target complexity,* as well as *product and product portfolio complexity* (Bliss, 2000; Gießmann, 2010; Lasch & Giessmann, 2008; Marti, 2007; Schömann, 2012) and can be extended by the category of *technological complexity (internal)* (Grimm et al., 2014; Keuper, 2004; Schoeneberg, 2014). This can be further extended by *product development complexity* (Bayer, 2010; Dehnen, 2004; Jongbae Kim & Wilemon, 2003), *supply process complexity* (Bayer, 2010; Blockus, 2010; Nurcahya, 2009), *service complexity* (Collinson & Jay, 2012; Dalhöfer, 2009; C. Schmidt et al., 2008), and *remanufacturing complexity* (Bayer, 2010; Haumann et al., 2012)[3]. The category of *correlated complexity* comprises eight clusters.

[1] For further description of market complexity refer to Schoeneberg (2014), Grimm et al. (2014), and Gießmann (2010)

[2] For further description of technological complexity refer to Blockus (2010) and Schömann (2012)

[3] For further description of remanufacturing complexity refer to Seifert et al. (2013) and Steinhilper et al. (2012)

The subcategory of *internal autonomous complexity* consists of seven clusters. *Organizational complexity* and *process complexity* are described by various authors (Gießmann, 2010; Lasch & Giessmann, 2008)[4]. In the literature, the subcategory also includes *structural complexity* (Gießmann, 2010; Lasch & Giessmann, 2008; Schoeneberg, 2014), whereas several authors put it into the cluster of organizational complexity (Kersten et al., 2006; Lindemann et al., 2009; Serdar-Asan, 2013).

The subcategory *internal autonomous complexity* can be extended by *production complexity* (Bliss, 1998, 2000; Keuper, 2004; Westphal, 2001)[5]*, planning, control and information complexity* (Keuper, 2004; Mayer, 2007; Ruppert, 2007)[6], *resource complexity* (Bohne, 1998; Höge, 1995), as well as *sales and distribution complexity* (Bayer, 2010). Additionally, a so-called cluster of *general complexity* is described in the literature (Denk & Pfneissl, 2009; Kersten et al., 2006; Mayer, 2007).

2.5 Literature review

Before conducting research, it is crucial to identify the body of knowledge using a literature review in the related field (Webster & Watson, 2002, p. 13).

The author of this dissertation chose the approach published by Levy and J. Ellis (2006), which is structured into three steps:

- First, identify the relevant literature – the input – for the research topic by choosing relevant journals, keywords, and literature vendors.
- Second, process the data of the sources into information to build up a basis for new research (Bem, 1995).
- Third, summarize the results of the literature analysis.

[4] For further description of organizational complexity and process complexity refer to Grimm et al. (2014), Schoeneberg (2014), and Schömann (2012)

[5] For further description of production complexity and process complexity refer to Götzfried (2012), Schömann (2012), Lasch and Giessmann (2008), Bayer (2010), Marti (2007), and Mayer (2007)

[6] For further description of planning, control and information complexity refer to Grimm et al. (2014), Lasch and Giessmann (2008) Schoeneberg (2014), and Schömann (2012)

2.5.1 Literature input

Literature input includes selecting the literature databases, journals, and the process of "gathering manuscripts" (Levy & J. Ellis, 2006, p. 185). The present author sourced operations management journals to accumulate relevant contributions and obtain an overview of the literature field.

This research also used well-known peer-reviewed conference papers, despite their commonly regarded lower overall rigor compared to journal papers, to get access to recent developments in the field of mastering complexity. The list of journals and the applied keywords are presented in Appendix A.

2.5.2 Literature processing

The literature review process includes "sequential steps to collect, know, comprehend, apply, analyze, synthesize and evaluate quality literature" to establish knowledge regarding a topic being newly researched on (Levy & J. Ellis, 2006, p. 182). The present dissertation is based on two literature reviews.

The first literature review aimed at identifying the body of knowledge regarding methods of mastering complexity and their relationship to complexity drivers. Eight relevant articles were identified. A total of 19 methods related to mastering complexity are described in these articles. Subchapter 2.6 elaborates on the results of this literature review. The figures regarding the assignment of the identified methods to the publications, the search string, and the number of identified and relevant articles can be found in Appendix A.

The second literature review investigated existing publications regarding the topic of identifying and conceptualizing methods for mastering complexity. Nine articles were identified as relevant to the topic of influencing factors for identifying and conceptualizing methods for mastering complexity in the manufacturing industry. The tables of the literature review, including the search string, the journals, and the number of identified and relevant articles are presented in Appendix A. This search was complemented with a forward and backward search within the relevant articles. Individual sources focused on the isolated mastering of complexity and application of methods. Regarding the integrated view of a manufacturing company and influencing factors for identifying and conceptualizing suitable methods for mastering its

complexity, only a few articles were found. These articles are discussed in subchapter 2.7.

2.5.3 Literature output

Literature output encompasses the writing of the literature review. Based on the first two steps – literature input and processing – detailed knowledge was gathered in the field of complexity management. The application of keywords resulted in relevant articles, which are analyzed in subchapters 2.6 and 2.7.

2.6 Literature on methods for mastering complexity

In this subchapter, first the results of the literature review regarding the methods for mastering complexity are outlined (subchapter 2.6.1). Subchapter 2.6.2 applies a funnel to derive a selection of methods for mastering complexity for the quantitative study in Chapter 3. The author describes the characteristics of these methods in subchapter 2.6.3. Subchapter 2.6.4 focuses on the relationship of the methods to complexity drivers, as found in the literature.

2.6.1 Results of the literature review

The author conducted a literature review according to the process described in subchapter 2.5, aiming to identify methods for mastering complexity in the manufacturing industry and the relationship of these methods to complexity drivers. This research focused on operations management journals as suitable literature input for relevant contributions regarding methods for mastering complexity. The result of the review process is described below.

First, a literature search was conducted. The relevant journals and the search string to identify the relevant publications and methods for mastering complexity in the manufacturing industry are outlined in Appendix A.

This list is complemented by interviews, discussions, and workshops with practitioners and researchers. The resulting list of methods represents those most commonly

described in relationship to mastering complexity.[7] Table 7 shows the identified 21 methods for mastering complexity and the linked literature[8]. The relevance of these methods for this dissertation is evaluated based on a funnel model that integrates several iterative discussions with researchers and practitioners.

[7] This dissertation focuses on the methods for mastering complexity along the value chain. Methods to measure complexity are outside of the scope of this dissertation and can be looked up, e.g., in the following publications: Budde (2016); Götzfried (2012); Heina (1999); Nussbaum (2011); Orfi et al. (2011); Rennekamp (2013).

[8] For further description of the methods refer to the basic literature which might not have been identified in the literature review: *ABC Analysis*: Cordts and Lensing (1992); *Conjoint Analysis*: Luce and Tukey (1964), Green and Rao (1971); *DFV:* Martin and Ishii (1996); *FMS:* Koren (2005); *Global management of product platforms*: Dahmus et al. (2001), M. Meyer et al. (1997); *Mass customization:* Pine (1993); *MFD*: Erixon (1998); *Modularity of production:* Koren (2005); *Modularity of products:* Baldwin and Clark (1997), Göpfert (1998); *Product configurator*: Redlein (1999), Forza and Salvador (2008); *Product portfolio management:* R. G. Cooper (1999), M. A. Jacobs and Swink (2011); *VMEA:* Caesar (1991), Schuh (1989); *QFD:* C.-C. Chen (2010); *Requirements Engineering*: Heumesser and Houdek (2003), Pohl and Rupp (2015); *RMS:* Koren (2005); *Standardization of production processes:* Vries (1999); *Standardization of products:* Perera et al. (1999); *Product families*: Dahmus et al. (2001), M. Meyer et al. (1997).

Table 7: Results of the literature review of methods for mastering complexity

Methods	Source: H. ElMaraghy et al. (2013)	W. ElMaraghy et al. (2012)	Keckl et al. (2016)	Landherr and Westkämper (2014)	Theuer and Lass (2016)	Mourtzis and Doukas (2014)	Perona and Miragliotta (2004)	Jagersma (2008)
Modularity of Products	•	•		•			•	
Standardizing Products	•							•
Modularity of Production			•	•	•	•		
Standardization of Production	•							•
Requirements Engineering	•	•						
Product Portfolio Management	•							•
Modular product platforms	•	•						
Product configurator				•				
DFV	•							
QFD	•							
Conjoint analysis	•	•						
Mass customization	•	•						
MFD	•							
Product families	•							
RMS	•		•	•		•		
FMS				•				
Postponement	•							•
Customer value-oriented product portfolio		•						
Autonomous production systems					•			
VMEA*								
ABC analysis*								

** The method included is based on discussions and workshops with researchers and practitioners*

Methods for mastering complexity can be categorized according to their influence on the value chain. Researchers differentiate between market, product, and manufacturing and supply chain complexity (W. ElMaraghy et al., 2012; Wildemann & Voigt, 2011). Figure 3 shows the clustering of the methods according to their influence on the value chain.

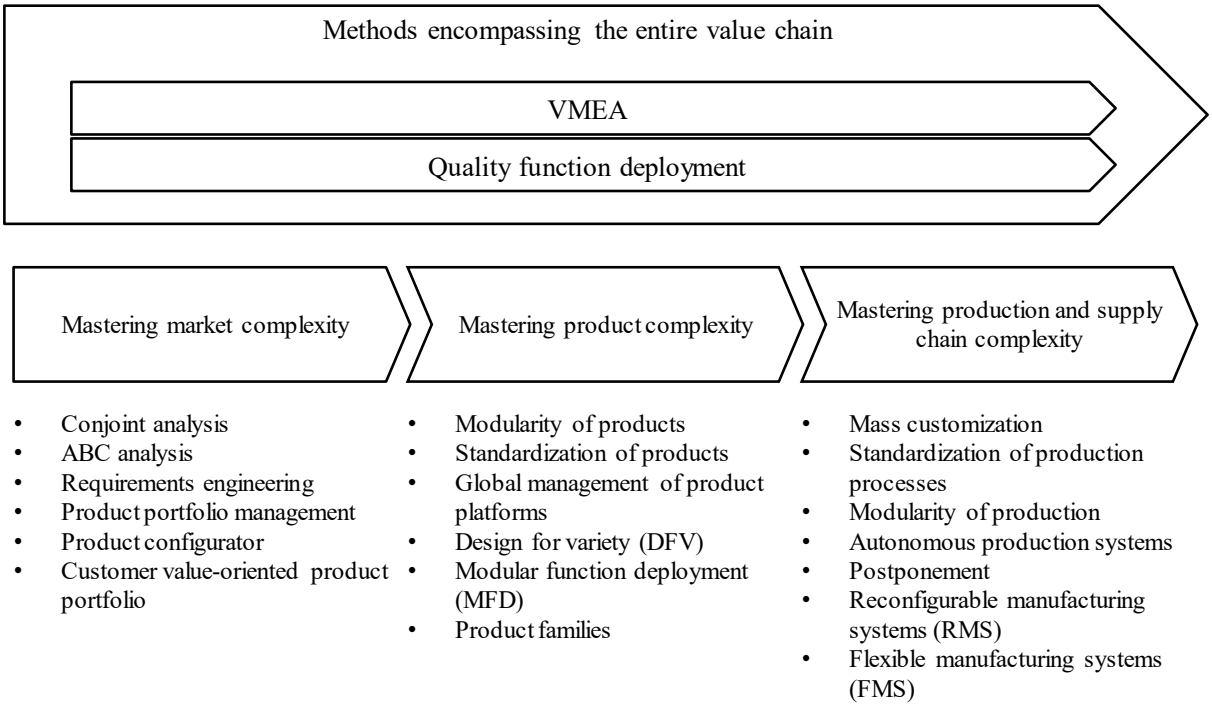


Figure 3: Categorization of methods for mastering complexity

In the subsequent subchapter, the methods to be investigated in the quantitative study in Chapter 3 will be selected using a funnel model.

2.6.2 Funnel model: Selecting methods for mastering complexity

The previously shown methods state approaches for mastering complexity. To allow an analysis of the implementation degree, this dissertation focuses on a particular selection of methods. To derive this selection of methods the research team applied a funnel model. In the following subchapter, the funnel model, as well as the chosen filter criteria in this research project, are described.

Researchers describe the funnel model as a method for selecting alternatives in development projects (O'Sullivan, 2002; Wheelwright & Clark, 1992). Therefore, the funnel aims at regulating the number of innovations in the organization. Resources and

controls define the neck of the funnel to narrow down and manage the number of outcoming innovations (O'Sullivan, 2002, p. 81).

The methods for mastering complexity were identified based on literature research and iterative interviews with executives of manufacturing companies and researchers. After having narrowed down the number of possible methods, the results in this chapter can be seen to derive from a funnel model developed with a four-step procedure. First, some methods were eliminated based on the focus of this dissertation on individual methods along the value chain. Second, the number of methods was further reduced due to the redundancy and clustering based on the interdependency of these methods. Third, methods were selected based on their occurrence in literature. Fourth, the relevance of the methods for this dissertation was evaluated based on iterative exchanges with executives and researchers regarding two criteria which were observed at the necks of the funnel, and which will be described in the following subchapters.

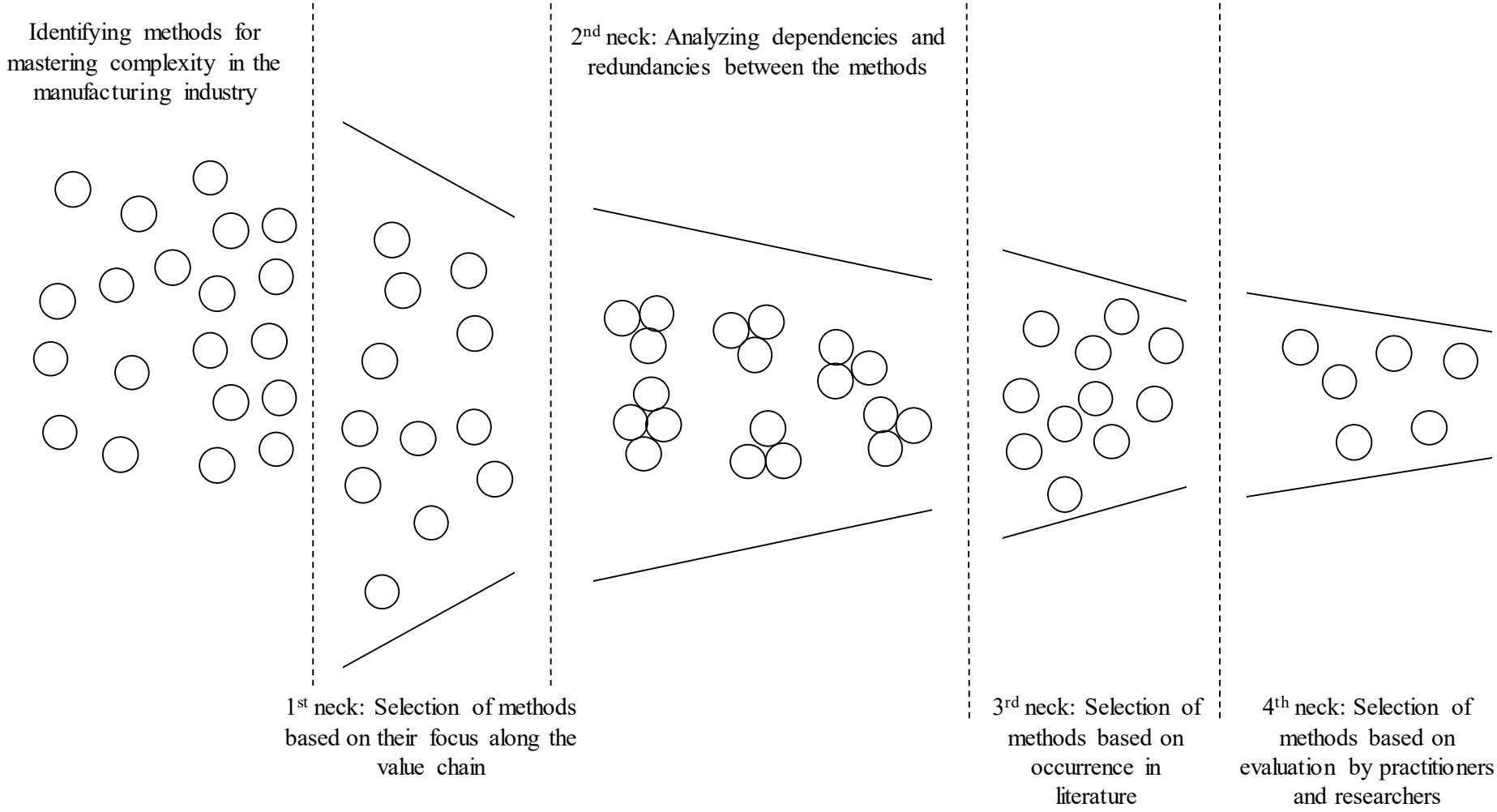


Figure 4: The funnel model used in this dissertation

2.6.2.1 Selection of methods based on their focus along the value chain

The methods identified in the literature review in subchapter 2.6.1 are assigned to individual stages along the value chain. The methods, VMEA and QFD, are assigned to the entire value chain. VMEA and QFD, both are a framework integrating a selection of methods for mastering complexity. This dissertation focuses on individual methods assigned for mastering market, product as well as production and supply chain complexity, as shown in Figure 5. Therefore, the list of methods is reduced from 21 to 19.

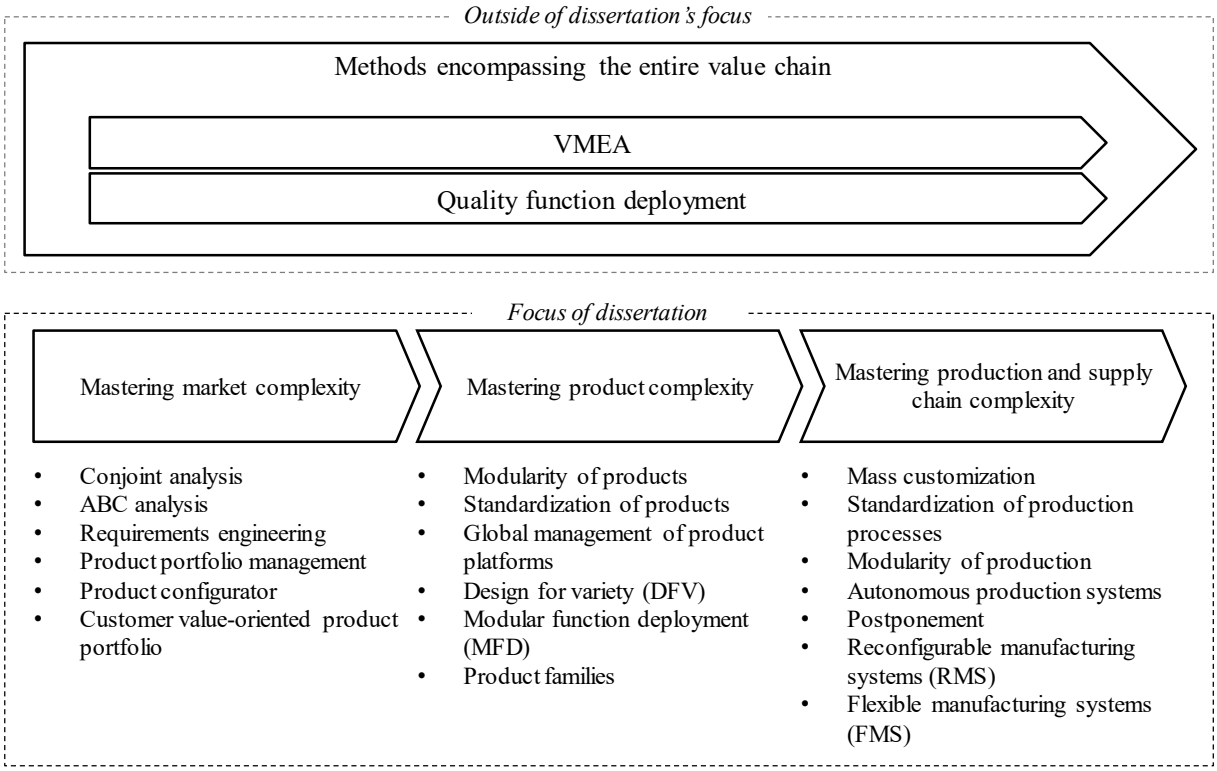


Figure 5: Selection of methods after first neck of the funnel model

2.6.2.2 Analyzing dependencies and redundancies between the methods

Based on literature, as well as on discussions with researchers and practitioners, this subchapter identifies overlapping and similar targets, along with dependencies between the methods for mastering complexity. Figure 6 shows the filtering of methods at the 1st neck.

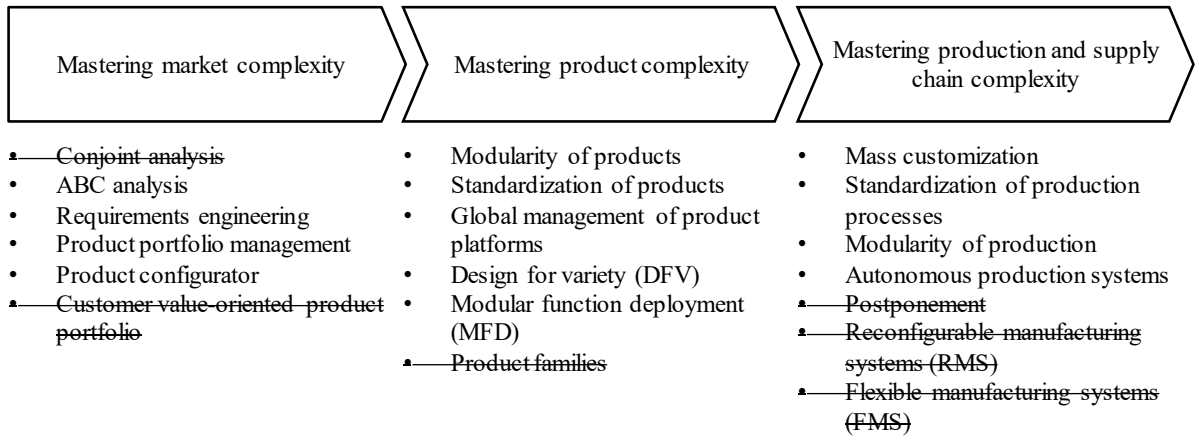


Figure 6: 1st neck: Filtering of methods based on dependencies

The concepts of *RMS* and *FMS* have not yet been implemented in most manufacturing companies and still need to be adapted to practical circumstances. Hence, our research team focused on a critical enabler to achieve a higher implementation degree of reconfigurable (RMS) and flexible manufacturing systems (FMS) [9] in the manufacturing industry. Modularity of production is regarded as an enabler for RMS and FMS. Through the modular design of machines and production processes, an increase of reconfigurability is achieved. As a result, the manufacturing processes are able to react to demand changes and to produce product variants with higher flexibility. Hence, the research team chose modularity of production as the method for investigations in the research study.

Postponement has been characterized as one principle of demerging production processes[10]. It allows for keeping production processes standardized as long as possible, to reduce the process variety and production costs. The modularity of products and production are enablers for postponement. Therefore, this dissertation investigates these enablers instead of the concept of postponement.

The methods *customer value-oriented product portfolio,* along with *conjoint analysis*, are closely related to *product portfolio management*. As product portfolio management is regarded as the general method to derive a suitable product offering for customers, it is the focus in this dissertation.

[9] For further details see detailed description of modularity in production in subchapter 2.6.3.3.

[10] For further details see detailed description of postponement in subchapter 2.6.3.3.

Product families[11] consist of a set of differentiated products and allow for targeting diverse customer requirements on various markets more efficiently. The differentiated products in one family are based on a product platform. By applying the concept of *product platforms*, combined with modularity of products, the difficult efforts to develop product families can be decreased. Hence, the methods of product families, modularity of products, and product platforms are closely linked. Based on discussions with researchers and practitioners, modularity and product platforms have been proven in this dissertation to be more relevant than product families for mastering complexity. Therefore, the investigation of these two methods was focused on in this research study.

Based on the identified dependencies and redundancies, this subchapter narrows down the number of methods from 19 to 13. Figure 7 shows the results after clustering of interrelated methods. In total 13 methods will be regarded at the 2nd and 3rd necks to identify the relevant methods for mastering complexity.



Figure 7: List of methods after 1st neck and clustering

2.6.2.3 Filtering based on literature occurrence

The 2nd neck reduces the number of methods, based on its occurrence in literature. This dissertation focuses on methods that occur more than once in publications identified in the literature review in subchapter 2.6.1. Figure 8 shows the filtering of methods at the 2nd neck.

[11] For information and descriptions of product families refer to Du et al. (2016); Jiao and Tseng (2000); Bryan et al. (2013).



Figure 8: 2nd neck: Filtering of methods based on literature occurrence

The methods *DFV* and *MFD* occur only once in a publication by H. A. ElMaraghy et al. (2013). *Product configurator* is only once described, in the publication by Landherr and Westkämper (2014). *Autonomous production systems* only occurs once, in Theuer and Lass (2016). Therefore, these methods are outside of the dissertation's focus.

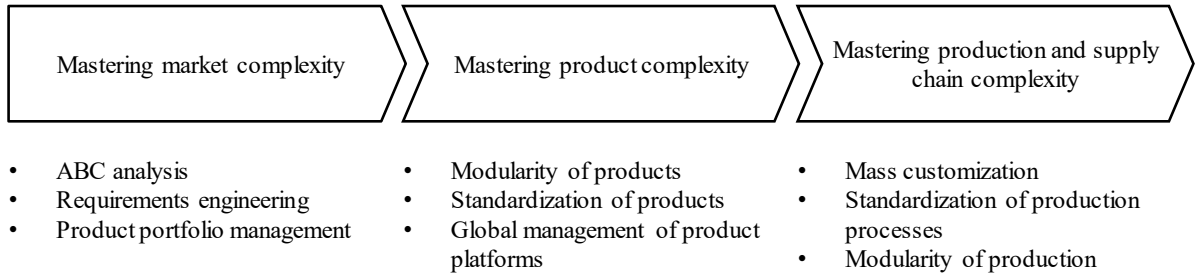


Figure 9 visualizes the remaining nine methods after the 2nd neck.

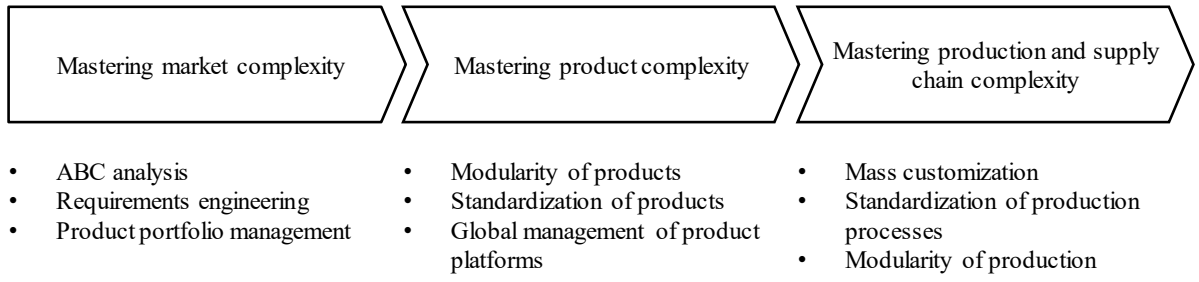


Figure 9: List of methods after 2nd neck

2.6.2.4 Evaluation by practitioners and researchers

Additionally, to derive the final selection of methods for the benchmarking study the research team iteratively discussed current methods and evaluated their relevance with experienced researchers and practitioners. Sixteen executives from international manufacturing companies, and six researchers, were involved in workshops and semi-structured interviews to evaluate the methods regarding the following two criteria:

- Relevance for mastering complexity in the manufacturing industry

- Applicability in the manufacturing industry

The criteria *relevance for mastering complexity in the manufacturing industry* builds upon the definition of mastering complexity from subchapter 1.1. It is evaluated from the perspective of academics and practitioners and is based on the evaluation of experienced researchers and executives from the field of complexity management in the manufacturing industry. The results of papers, as well as experiences in manufacturing companies, were considered, along with the identified methods for mastering complexity. The *applicability within the manufacturing industry* was regarded mainly from a practitioners' viewpoint. The ease of applying the method (for example, the amount of preparation for the method needed in the manufacturing industry) was taken into consideration.

In the following section, the methods shown in Table 8 are evaluated, especially with regard to the two criteria, in order to derive a selection of methods for the study in Chapter 3.

Table 8: Classification and evaluation of methods for mastering complexity

Methods	Relevance for mastering complexity in the manufacturing industry	Applicability in the manufacturing industry	Result
Mastering market complexity			
ABC analysis	◔	◑	◔
Product portfolio management	◕	◑	◕
Requirements engineering	◕	◕	◕
Mastering product complexity			
Global management of modular product platforms	◕	◑	◕
Standardization of products	◔	◑	◔
Modularity of products	●	◕	●
Mastering production and supply chain complexity			
Mass customization	◑	◑	◑
Standardization of production	◑	◑	◑
Modularity of production processes	●	◔	◕

○	very low
◔	low
◑	medium
◕	high
●	very high

The Method *ABC analysis* is rated on a low level with respect to its *relevance for mastering complexity in the manufacturing industry*, as it visualizes the contribution of the existing product portfolio to performance indicators based on the pareto principle. Based on the result, the focus of the company shifts to the products with high contribution. Therefore, this method does not support the target of mastering complexity while at the same time fulfilling customer requirements with an optimized product portfolio. In most cases the sales of product variants are interrelated. Elimination of product variants from the product portfolio can negatively impact the overall sales of a company. Since identifying the correct product variants to be eliminated from the product portfolio without negatively affecting sales numbers of other product variants is tricky, *the applicability in the manufacturing industry* is rated medium.

Product portfolio management supports aligning the product portfolio with the strategic orientation of the company or business field. It helps to understand the interrelation of the methods and their relationship to the targets of the organization. Through its

strategic, long-term character it supports the mastering of nascent complexity and is therefore rated on a high level regarding *relevance for mastering complexity*. There are no dedicated frameworks or guidelines regarding how to successfully manage a company's product portfolio. The identification of interrelationships of the products and their variants requires experience and effort. Therefore, the method is rated on a medium level regarding the *applicability in the manufacturing industry*.

An organization applies *requirements engineering* to analyze the relationship of requirements from customers, regulatory, and internal stakeholders along the value chain to characteristics of products and processes. Since the different requirements and their management affect the complexity of a manufacturing company the *relevance for mastering complexity* is rated highly. Applying requirements engineering is accompanied by considerable efforts. The relationship of requirements to characteristics of products and processes, as well as the interdependency of the requirements themselves, can be identified with dedication and a structured process. The *applicability in the manufacturing industry* is therefore given high priority.

The method *global management of modular product platforms* facilitates the development of a global product portfolio anchored to a modular product platform. The ability to manage product platforms for global customer requirements results in a high rating of *relevance for mastering complexity*. Since, the alignment of these requirements to derive a global product platform is not supported by a clear, structured process and guidelines, the correct application is dependent on the individual company and presupposes substantial effort and dedication. Therefore, the *applicability in the manufacturing industry* of the method is rated as medium.

Standardization of products supports mastering complexity along the product lifecycle and the production processes by identifying standardized components across the product portfolio. As standardization is the first step of modularizing products it is considered as inferior compared to modular product structures making the *relevance for mastering complexity* low. The *applicability* of the methods is rated medium, as not every manufactured product is suitable for standardization.

The concept of *modularity of products* helps to structure the products into independent parts in order to relate each part to one product function. Modular products are therefore suitable to flexibly match products with individual customer needs. The rating of *relevance for mastering complexity* is therefore on the level 'very high'. For a manufacturing company to apply the concept of modularity to its products depends on

the products themselves and involves great efforts for implementation. Nevertheless, many implementations in the industry can be identified and, as a result, the *applicability in the manufacturing industry* is rated high.

Mass customization is a method aiming to combine producing efficiently through economies of scale and delivering individualized products. The company focuses on individualized characteristics rated with the highest priority for the customer which are produced through mass production to increase efficiency. As a result, the method is rated on a medium level in *relevance for mastering complexity*. In the literature, three scenarios are described which support users in identifying whether mass customization is a beneficial method in their situations. Nevertheless, the method lacks a structured process for application, and is rated as 'medium' regarding the measure *applicability in the manufacturing industry*.

The *standardization approach of production processes* supports companies in identifying common elements for deriving a standard across all processes. Standards in production processes help to minimize the number of variances, and therefore lower the manufacturing time per product and setup time between products. As a result, the manufacturing processes can be designed independently of products, which allows higher flexibility. Nevertheless, standardizing production processes is the first step towards modularity of production processes and is rated with a lower impact on mastering complexity. Standardization of production processes is rated as medium regarding the criteria of *mastering complexity in the manufacturing industry*. Since the suitability of the method depends on the structure of the company's products and processes, the *applicability* is rated on a medium level.

Modularity of production processes supports manufacturing companies by enhancing their flexibility in producing a high variance of products. It enables companies to add or remove parts of a manufacturing system without influencing other parts of the system. Thus, the manufacturing processes can be flexibly adapted to produce different product lines. The method is rated as 'very high' regarding the *relevance for mastering complexity in the manufacturing industry*. Since there are no clearly structured processes or guidelines to apply modularity of production processes to, and the suitability is dependent on the structure of a company's products and processes, the *applicability in the manufacturing industry* is rated 'low'.

Based on the elaboration above, the methods are rated regarding the two criteria *relevance for mastering complexity in the manufacturing industry* and *applicability in*

the manufacturing industry. This dissertation focuses on methods rated higher than 'medium' in average overall criteria. Figure 10 shows the filtering of the methods based on the 3rd neck.

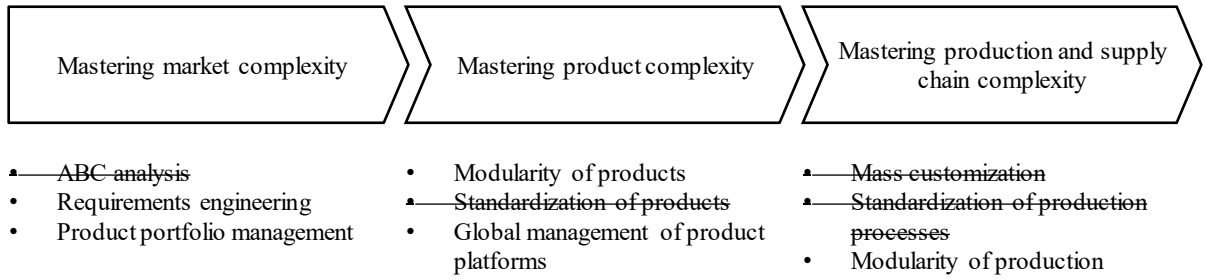


Figure 10: 3rd neck: Filtering of methods based on evaluation by researchers and practitioners

Based on the average evaluation from researchers' and practitioners' overall criteria, the final selection of the methods can thus be derived (see Figure 11). As a follow-up result, *modularity of production, modularity of products, global management of modular product platforms, requirements engineering,* and *product portfolio management* will be investigated in Chapter 3.

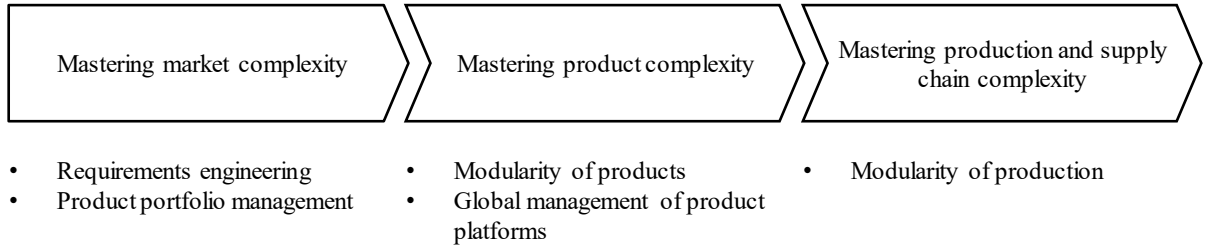


Figure 11: Final list of methods after the 3rd neck

2.6.3 Description of final selection of methods for mastering complexity

In this subchapter, the methods with the highest average evaluation throughout all criteria are assessed. The methods are assigned to the categories of *mastering market complexity, mastering product complexity,* and *mastering production and supply chain complexity*.

2.6.3.1 Mastering market complexity

This subchapter describes the methods in focus of this dissertation for mastering market complexity (see Figure 12). Variety, diversity, and interrelatedness of customer

requirements cause increased market complexity. Market complexity influences the product portfolio offered by a company.



Figure 12: Methods within the focus of this dissertation – mastering market complexity

Requirements engineering

Requirements engineering is an important aspect of high-quality product development. In general, the activities of requirements engineering encompass the identification, documentation, validation, and management of the system objectives (Pohl & Rupp, 2015, pp. 4–5). Applying these activities in industrial cases results in individual challenges, for example, permanent enhancement and late modification of the objectives or the number of stakeholders involved in the process (Heumesser & Houdek, 2003, p. 4).

Especially in complex systems with a high level of uncertainty, ambiguity, and emergence, specific tools for requirements engineering are needed (Katina et al., 2014, pp. 45–46). The applied tools should take into consideration the impacts of the role of the system observer, the nature of system requirements, and the nature of the environment within the requirements engineering process (Katina et al., 2014, p. 60). As a result, a holistic perspective helps to deal with requirements in complex conditions (Katina et al., 2014, p. 60).

Product portfolio management

The product portfolio is characterized by a variety, diversity, and interrelatedness of products (M. A. Jacobs & Swink, 2011, p. 677). Product portfolio managers determine the list of products offered by the company to compete on the market (Jugend et al., 2016, p. 5095). A customer value-oriented product portfolio aims at eliminating all product variants not contributing to the customer needs (Rebentisch et al., 2016, p. 82). R. G. Cooper (1999, p. 334) places much emphasis on product portfolio management and states its three main tasks:

- Prioritizing and selecting the products which support the operationalization of the business strategy;
- Decision-making relative to future products and technologies, which will influence the future of the company;
- Allocation of resources along the value chain.

2.6.3.2 Mastering product complexity

This subchapter describes the methods for mastering product complexity (see Figure 13). In order to holistically manage the impact of complexity on an organization, product complexity takes on a critical role. It determines the variety on the module and component level as well as the complexity in manufacturing processes. Product complexity demonstrates the ability of a manufacturing company to decouple external from the internal complexity. Through an innovative product structure, highly individualized customer demand can be handled while retaining low product complexity.



Figure 13: Methods within the focus of this dissertation – mastering product complexity

Modularity of products

Baldwin and Clark (1997, p. 84) describe modularity as the process of *"building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole."*

Göpfert (1998, p. 104) adds two dimensions when defining the modularity of physical products. The functional independence of components means one component can fulfill its function independently from the other. The possibility of physically separating components from each other is referred to as the second dimension (Göpfert, 1998, p. 106). The modularity of systems leads to fragmentation into subsystems which interact with each other (Göpfert, 1998, p. 34).

Per definition, the process of modularization creates subsystems, individual "modules". Schaefer (2007, p. 21) defines a module as *"...a controllable, reprogrammable, reusable, and reconfigurable, portion of a system, with process-oriented functionality and well-specified interfaces that carries out a specific function and may be used alone or combined with other modules of the given system."*

The design and development process of products may primarily be influenced by the concept of modularity (Salvador et al., 2002; Ulrich, 1995). According to Baldwin and Clark (1997), modularity is a specification of a complex system that aims at structures with a minimum of interdependencies between its components, increasing the interdependency within them to a maximum. Additionally, each module within a complex system with a high level of modularity communicates with the others via standardized interfaces, which also allows for a decoupling of modules (Baldwin & Clark, 1997).

Modularity permits the design of product variants using common units. Therefore independent, standardized, or interchangeable units need to be identified to create various functions (C.-C. Huang & Kusiak, 1998, p. 66). To plan product variants more efficiently and to achieve economies of scope, product family architectures are designed based on product modules (AlGeddawy & ElMaraghy, 2012; H. A. ElMaraghy, 2009b). Ulrich (1995) describes the impact of modularity in combination with product architecture. The product architecture is the arrangement of functional elements, the assignment of functional elements to physical components, and the determination of interfaces of related physical components (Ulrich, 1995, p. 420). In a modular product architecture, the functional elements are mapped in a one-to-one relationship to the physical components, and the interfaces are designed to allow de-coupling of the components (Ulrich, 1995, p. 422).

In conclusion, modularity in products permits the independent design of components of a complex product by decomposing the elements into functional subsystem units (Baldwin & Clark, 1997, p. 84). This allows the company to develop and produce these individual units independently, integrating them into different products to reduce complexity while at the same time increasing functionality (Baldwin & Clark, 1997, p. 85). Modularity can be used to enable companies to capture individual customer

demands while minimizing their costs in development and production throughout the whole life cycle (Gershenson, 1997, p. 2).

Global management of product platforms

To meet the demands of diverse global markets, companies develop *product families*. A *product family* consists of a selection of differentiated products aiming to satisfy different market needs. The differentiated products in one *family* are based on a product platform. By applying the concept of product platforms combined with modularity of products, efforts to develop *product families* can be decreased (Dahmus et al., 2001; M. Meyer et al., 1997). To ensure global commonality and compatibility, the *product platform* and the related elements need to have standard interfaces (K.-M. Chen & Liu, 2005, p. 774). Based on the common interfaces, the component development processes for a global product portfolio can be decoupled, allowing for increases in the rate of innovation (Sanchez, 1999).

2.6.3.3 Mastering production and supply chain complexity

Along with the increasing product variety tailored to individual customer demands, challenges occur in the manufacturing processes (H. A. ElMaraghy & Wiendahl, 2009). To remain competitive, these challenges need to be managed through responsiveness to volatility and capability of manufacturing a high variety of products (Brunoe et al., 2017, p. 205). The following section outlines methods for mastering the complexity within the production and supply chain (see Figure 14).



Figure 14: Methods within the focus of this dissertation – mastering production and supply chain complexity

Modularity of production

Modularity is described as an enabler for *reconfigurable and flexible manufacturing systems (RMS & FMS)* (Koren, 2005; Nyhuis, 2008; Wiendahl et al., 2007). RMS are

capable of fulfilling some of the requirements for changeability[12]. To allow the RMS to react to fluctuation in demands with precise flexibility, the systems need to be designed while considering the following key characteristics: modularity, integrability, customization, scalability, convertibility, and diagnosability (Koren, 2005; Nyhuis, 2008; Wiendahl et al., 2007). According to Koren (2006), these characteristics can be applied to the design of the whole production system and its machines, and the characteristics can be differentiated into "sufficient" and "necessary" conditions of RMS. Thus, customization, scalability, and convertibility are defined as essential (necessary) characteristics, while modularity, integrability, and diagnosability are supporting (sufficient) characteristics, reducing the time for system reconfiguration and ramp-up (Koren, 2006).

Koren (2005, p. 2) describes modularity in a manufacturing context as the compartmentalization of operational functions and requirements into quantifiable units that can be transacted between alternative production schemes to fit a given set of needs. Modularity in production can also be described as the aim of organizing the manufacturing process in a way to increase flexibility and to allow a reduction of complexity. Production processes are organized in standardized, autonomous units including defined strong organizational connections (M. Jacobs et al., 2011).

Feitzinger and Lee (1997, p. 119) describe three principles for demerging the whole production process into independent sub-processes: process postponement, process re-sequencing, and process standardization. *Process postponement* allows shifting order-dependent sub-processes to a later point in time, when a customer places an order, or it can mean transferring those process modules to distribution centers (Köster, 1998, p. 83; Schuh, 2005, p. 177). Bringing the sub-processes into a new order, so that standard processes are at the beginning of the production process and customization sub-processes at the end, is referred to as *process re-sequencing* (Feitzinger & Lee, 1997, p. 119). *Process standardization* divides the manufacturing process into two main modules, one for standardized components and one for individualized customer elements (Feitzinger & Lee, 1997, pp. 119–120). Hence, modular production allows

[12] The term changeability relates to the manufacturing system that makes various workpieces, along with the whole factory that produces different products in multiple variants. For a detailed description refer to H. A. ElMaraghy (2009a).

resequencing and tooling with little functional loss (Schilling & Steensma, 2001, p. 1151).

2.6.4 Relationship of methods to complexity drivers

This subchapter describes input from the literature regarding the relationship of the final selection of methods to complexity drivers. Table 9 shows the identified relationships based on literature research.

Table 9: Relationship of methods and complexity drivers in the literature

	Methods				
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*
Variety of products			•	•	
Variety of customer requirements	•	•	•	•	•
Number of customers		•	•		
Volatility of customer demand	•	•			•
Dynamics of competition	•				
Dynamics of product portfolio			•	•	
Organizational structure		•			
Dynamics of product technology	•	•	•	•	
Political factors					•
Dynamics of production technology			•	•	

Manufacturing companies need to consider the internal and external complexity drivers along the whole value chain, in order to deliver highly customized products. The value chain consists of the development and the production of products as well as of logistics. Levers to master these challenges include the design of business processes, product

structures, and supply chains, as well as the production network and production methods. (H. A. ElMaraghy, 2009a, p. 6)

Modularity of products

Topic-related literature describes a positive relationship between the implementation degree of modularity in products and processes and *heterogeneity in customer demand,* as well as *technological complexity* (Baldwin & Clark, 1997, p. 85; Sanchez & Collins, 2001, p. 648). Modularity of products can be used to enable companies to capture individual customer demand while minimizing their costs in development and production, along the whole life cycle (Gershenson, 1997, p. 2). H. A. ElMaraghy and Wiendahl (2009, p. 35) describe the ability of companies to offer wide product varieties through the use of modular product structures.

Global management of modular product platforms

One topic of importance in the reviewed literature concerns the use of global modular product platforms, mainly in the context of highly *individual customer demand*, wide *variety of products*, and high *dynamism regarding product and production technology* (Dahmus et al., 2001, pp. 409–410; M. Meyer et al., 1997, p. 36). According to Dahmus et al. (2001, p. 409), a common platform supports differentiating the products effectively, in order to fulfill individual customer demands. They illustrate this relationship with Volkswagen's platform and component commonality for its front and rear axles, exhaust systems, brake systems and many other elements used in VWs, Audis, Seats, and Skodas (Dahmus et al., 2001, p. 409). This has led to companies increasing their competitive advantages through the global management of modular product platforms (Sanderson & Uzumeri, 1995, p. 766).

M. Meyer et al. (1997, p. 32) describe the ability of organizations to react to dynamism in the product portfolio, as well as in product and production technologies. The global management of modular product platforms enables companies to avoid high investments in dedicated tools and equipment, increasing the flexibility in the management of the product portfolio.

Product portfolio management

Diverse drivers of product portfolio complexity are described in some important literature sources. Closs et al. (2008, pp. 599–600) describe technological change created by stakeholders outside of the firm's control, and market diversity as important

drivers of complexity. Some authors propose the reduction of the product portfolio complexity in order to react to the increasing market diversity. They suggest eliminating products and product variants which contribute underproportionally to the revenue of the organization (Bliss, 2000, pp. 39–40).

Requirements engineering

In general, the activities of requirements engineering encompass the identification, documentation, validation, and management of the system objectives (Pohl & Rupp, 2015, pp. 4–5). Heumesser and Houdek (2003, p. 4) describe requirements engineering as an important method for managing the dynamics of product technologies, stakeholders' variability, and the volatility of their demands.

Modularity in production

Several publications describe the relationship between complexity drivers and modularity in manufacturing systems and processes. Individual customer demand requires current paradigms of production to change (Koren, 2005, p. 6; Matt et al., 2015, p. 185). Modular process architectures and the application of modularity principles in the design and operation of manufacturing systems can enable firms to increase speed and flexibility (Baldwin & Clark, 1997, p. 85; Koren & Shpitalni, 2010, p. 131; Sanchez & Collins, 2001, p. 648; Tu et al., 2004, p. 160). To produce a high variety of different products with a low product volume at reasonable costs, some firms apply modularity in manufacturing systems (Koren & Shpitalni, 2010, p. 131). The higher responsiveness allows the firm to react to political and legal market changes, as well as to increase the dynamism within the product portfolio (Koren & Shpitalni, 2010, p. 131).

These theoretical relationships were tested based on a quantitative study in Chapter 3, and based on case study research at five manufacturing companies in Chapter 4. Additionally, Chapter 4 also contains a description of an explorative approach to investigate the role of influencing factors, e.g., complexity drivers, for identifying and conceptualizing methods for mastering complexity.

2.7 Literature on identifying and conceptualizing methods for mastering complexity

Based on the structured literature review conducted in subchapter 2.5, this present subchapter describes the nine publications singled out in the field of identifying and

conceptualizing methods for mastering complexity[13]. Serdar-Asan (2009, 2011, 2013) focuses in her studies on identifying complexity drivers within the supply chain and the efforts as well strategies companies are applying to manage these drivers' influence.

In her paper, Serdar-Asan (2009) categorizes different complexity drivers, investigates supply chain management initiatives, and analyzes their contributions to managing the complexity within supply chains. As a main result, she develops a framework to support the decision-making process to define the elements of complexity management in the supply chain (see Figure 15) (Serdar-Asan, 2009, p. 6).

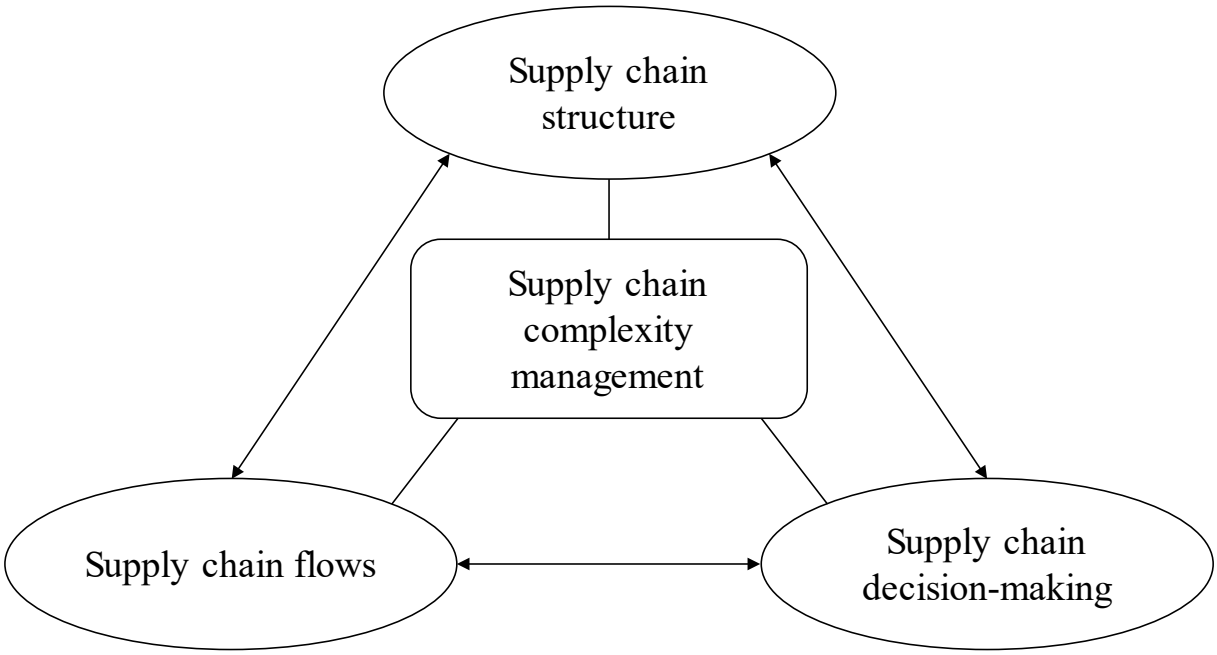


Figure 15: Framework of supply chain complexity management (Serdar-Asan, 2009, p. 82)

In her subsequent papers from 2011 & 2013, she reviewed the typical complexity drivers in supply chains from different industries, clustering them based on the origin and type of complexity. The types of complexity are divided into static, dynamic, and decision-making complexity, and the origin encompasses internal, supply/demand interfaces and external drivers (Serdar-Asan, 2013, p. 537). To identify good practices for managing complexity in the supply chain, she screened various reports of companies, consulting firms, service providers and other knowledge bases, including articles, books, case studies, industry reports, and conferences. As a result, 23 practices were identified which

[13] Refer to Appendix A for details regarding search string, the journals, and the number of identified and relevant articles.

suit the criteria of 1) being supply chain related, 2) having successful results, 3) providing the documents to continue with the survey (Serdar-Asan, 2013, p. 540). Furthermore, a matrix was created to match the types of complexity drivers with the identified solution strategies and supporting tools and technologies. (Serdar-Asan, 2013, pp. 533–540).

	SCM Initiatives	
	Solution strategy	*Supporting tools and technologies*
Static complexity	• Reducing the number of products • Reducing the options in the product and the SKUs (product complexity) • Reducing the number of outsourcing partners • Reducing the number of distribution centers	
Dynamic complexity	• Supply chain integration • Collaboration with suppliers, customers, and service providers • Supply chain visibility • Standardization of operations • Process automation • Synchronization of data • Information sharing • Logistics outsourcing • Planning on a daily basis • Process improvement and redesign	• VMI, CPFR • ERP software • Logistics management software • Supply chain planning software, APS • SRM software • WMS software • Transportation optimization software • IT service management solution • B2B platform • EDI • Barcoding, RFID • Profiling uncertain demand
Decision-making complexity	• Centralized decision-making • Automation of decision-making	• Business rules management system • SCM software

Figure 16: Complexity drivers, solution strategy, and tools and technologies (Serdar-Asan, 2013, p. 13)

Wildemann and Voigt (2011) developed a method to quantify individual external and internal complexity for small and mid-sized companies. Based on a literature review and case study analysis, a list of complexity drivers was derived. A method to evaluate the specific complexity of a company was developed which consists of 10 external (Wildemann & Voigt, 2011, p. 181) and 20 internal (Wildemann & Voigt, 2011, p. 209) complexity driver clusters. This method also includes individual determining factors from manufacturing companies. The authors also investigated the impact of complexity drivers on the processes within a manufacturing company. This analysis resulted in hypotheses, which were validated based on case studies and a quantitative study. The

results point to methods for managing complexity in the focal areas of product portfolio, processes, and organizational structure. Based on this work, a tool was developed to benchmark the complexity of different companies.

Größler et al. (2006) investigated the effects of increasing external complexity drivers on the adaptation processes in manufacturing firms. Within the study, a conceptual framework linking strategic manufacturing goals and complexity was developed. Hypotheses were statistically tested based on a data sample drawn from a survey regarding international manufacturing strategies. The results of the study indicate that manufacturing companies are confronted with different extents of complexity. Companies facing a high degree of complexity tend to establish more complex internal structures than companies confronted with lower levels of complexity. As a practical contribution, the developed conceptual framework includes the possibility of deriving a company strategy based on the level of complexity within its environment. (Größler et al., 2006, pp. 254–281)

Christopher (2012) described a model of supply chain capabilities for managing complexity. He analyzed the impact of "globalization of supply chains, continued outsourcing, and widespread adoption of lean practices" on the need to work interdisciplinarily, on employee and management skills, and on capabilities for understanding and managing complexity. Christopher proposed five key areas supply chain managers ought to be skilled in – tools and techniques of the day to day business, understanding of complex systems, process management on a horizontal level, effective leadership, and change management.

Dervitsiotis (2012) elaborated an approach for managing increasing external and resulting internal complexity. Differentiation in the product portfolio, processes, or business models to meet individualized customer demands creates complexity within an organization. He further analyzed methods for identifying complexity drivers, to reduce their impact. He described two main clusters of complexity drivers – "strategic complexity" and "operational complexity" (Heywood et al., 2007). "Strategic complexity" refers to the organization's structures as a result of strategic decisions regarding offered products, served markets, and technologies used. "Operational complexity" is described as the level of difficulty of the tasks of employees. Dervitsiotis (2012) suggests an approach consisting of four steps for mastering complexity. First, the unwanted complexity within the organization needs to be identified. Second, the organization can "eliminate, reduce or diffuse unwanted complexity" by, for example,

channeling complexity from a concentrated area to several skilled employees. Third, the organizational architecture needs to be analyzed, and if necessary, altered to meet changes in the business environment. Fourth, subsequent to changing the organizational architecture the business and production processes need to be analyzed for adaptation.

Kluth et al. (2014) introduced a maturity model for complexity management systems of manufacturing companies. The model supports managers in identifying the suitability of complexity management systems based on the individual complexity situation of the organization. Furthermore, the authors evaluated efficiency based on six levels of maturity. Level “Zero” is the stage of no understanding of complexity. On the first level – “Defined” – the company already has defined the external complexity drivers and its internal complexity fields. Companies with methods in place to qualitatively evaluate the complexity in the different complexity fields possess maturity level two “Qualitative”. Having a quantitative analysis based on KPIs is considered level three of the maturity model. On the fourth level – “Analyzed” – the company analyzes the internal complexity fields, including a correlation analysis of indicators. Having implemented “complexity cultivation strategies” for mastering the internal complexity a company has reached level five maturity – ”Managed”. Level six “Harmonized” describes the state of having optimized internal complexity, depending on the external complexity level, and includes the ability to adapt the internal complexity level dynamically (Kluth et al., 2014, p. 228).

- Scenario planning
  - Evaluating political, social and economic environment
  - Evaluating competitors
  - Identifying basic trends
  - Identifying major uncertainties
  - Identifying trigger (major) events
  - Creating a portfolio of options
  - Evaluating emerging markets
- Commitment centric leadership
  - Developing a clear vision
  - Clear purpose & principles
  - Communicating boundaries so everyone knows her/his limits
  - Inject change into organization
  - Balance order & disorder
  - Assign accountability for outcomes
  - Mold (pattern) the adaptive culture
  - Increase communication in the organization
  - Coordinate resources & projects
- Active planning
  - Monitoring political, social & economic environment
  - High interaction with customers
  - Interpreting patterns
  - Developing holistic perspectives
  - Watching for trigger events
  - Maintaining an outward view
  - Monitoring emerging markets
- Adaption
  - Sensing changes early
  - Meaningful interpretation of changes
  - Deciding on a course of action
  - Communicating implications of changes with employees
  - Focus on outcomes
  - Learning to improve the decision process
  - Acting on decisions
  - Reward system for responding to change
- Maintaining sustainability
  - Maintain delivering quality
  - Maintain good safety records
  - Maintain environmental procedures
  - Maintain training & developing employees
  - Make alliances or joint ventures if needed
  - Extensive suppliers /sub-contractors network
- Self-organization
  - Decentralized structure
  - Rewards based on team goals
  - Empowered teams
  - High levels of interaction
  - Aligning inter-department Goals
- Cost and expense control
  - Minimize overhead and office expense
  - Laying off unnecessary manpower
  - Control execution time
  - Control changes in running projects
  - Hiring necessary staff
  - Outsource costly tasks
  - Control scope in running projects
  - Control liabilities and debts

Figure 17: Framework for managing complexity in the construction industry (Shadid, 2018)

Shadid (2018) developed a framework to manage complexity in the construction sector. The framework aims to support managers and practitioners to “tackle uncertainty, unpredictability, disorder, rapid changes, and non-linearity” in complex environments. It consists of seven “prime principles” which are broken down into fifty “related elements” (Figure 17).

This subchapter described the result of a literature review with respect to the topic of influencing factors for identifying and conceptualizing methods for mastering complexity along the value chain of manufacturing companies. Partly related publications exist, but the topic has not yet been explicitly analyzed in specialist literature. Current literature mainly contains measurement models for complexity drivers or analyzes their effects on manufacturing strategies and goals.

2.8 Research gaps

Summing up, the literature review has indicated that there is a keen interest in the field of complexity management, especially in understanding and mastering complexity drivers within manufacturing companies (Maurer, 2017; Vogel & Lasch, 2016). Although the literature on complexity management encompasses publications from over 70 years (Maurer, 2017, p. 43), research regarding influencing factors for identifying and conceptualizing methods for mastering complexity is still missing. Since the methods for operations management have been studied thoroughly, their universal value is in doubt; instead, the application to specific contextual situations generally helps to increase performance (Sousa & Voss, 2008, p. 697). These authors maintain that the process of selecting methods for operations management needs to be studied in depth.

Existing publications address topics in the field of complexity management dedicated to individual stages along the value chain of manufacturing companies. The authors focus on the implementation and benefits of individual methods in the manufacturing industry. Especially the management of product complexity from a product architecture perspective has been overemphasized in the literature. Subchapter 2.6 described the methods for mastering complexity and their relationships to complexity drivers in the manufacturing industry. Relevant publications mainly describe the applicability of methods for mastering complexity, and their theoretical relationships as reflected in the literature; an evaluation of these relationships based on data from manufacturing companies is still missing.

This present dissertation aims at filling in the research gap of a structured analysis of the practical relationships between methods and complexity drivers. This Research focuses on identifying the implementation degree of methods, the most relevant complexity drivers and their relationships, based on quantitative data from the manufacturing industry. The relationships between methods for mastering complexity and complexity drivers has additionally been investigated using case study research from five manufacturing companies.

The topic of influencing factors for identifying and conceptualizing methods for mastering complexity along the value chain of manufacturing companies has not yet been explicitly analyzed in specialist literature. Subchapter 2.7 identified partly related publications based on a structured literature review. Complexity drivers within the supply chain and their impact on general strategies in individual aspects of the supply chain was analyzed by Serdar-Asan (2009, 2011, 2013). Manuj and Sahin (2011) described a model for identifying influencing factors of complexity in the supply chain and decision-making. Größler et al. (2006) investigated the link between external complexity and adaptation processes within manufacturing firms to derive a conceptual framework permitting implications for manufacturing firms' strategic goals as well as internal processes. Christopher (2012) identified five key areas of skills which fulfill chain managers requirements for mastering complexity. Supporting manufacturing companies in managing the increasing external and internal complexity is one of the specific goals of Dervitsiotis (2012). He described methods for identifying complexity drivers and methods for reducing their impact. Kluth et al. (2014) developed a maturity model for complexity management systems of manufacturing companies, to support managers in evaluating the suitability of methods to their complexity situation and its efficiency. The framework developed by Shadid (2018) explicitly supports companies in the construction industry with principles and subordinate principles for managing complexity.

However, an integrated perspective on influencing factors in manufacturing companies for identifying and conceptualizing methods for mastering complexity along the value chain is still missing. Current literature mainly contains measurement models for complexity drivers or analyzes their effects on manufacturing strategies and goals. The literature remains unclear regarding influencing factors for identifying and conceptualizing methods for mastering complexity within manufacturing companies (Serdar-Asan, 2013, p. 534; Sousa & Voss, 2008; Vogel & Lasch, 2016).

This research project intends to close these research gaps by applying a mixed-methods approach. Based on quantitative data and case study research with five manufacturing companies, the relationships of complexity drivers to methods for mastering complexity are analyzed. Furthermore, the insights from the case study research are utilized to investigate influencing factors for identifying and conceptualizing methods for mastering complexity. The insights from quantitative and qualitative research serve as a basis for developing a process model to support managers of manufacturing companies in identifying and conceptualizing methods for mastering complexity.

3 Quantitative approach

In this chapter, the quantitative approach used in our studies will be described, in order to answer SRQs 1-4. The chapter is divided into six subchapters. In subchapter 3.1, the survey design is detailed. Subchapter 3.2 focuses on the population and sample of the study. The instrumentation of the survey – comprising complexity drivers, the priorities and methods for mastering complexity – is described in subchapter 3.3. Subchapter 3.4 outlines the process of analyzing and interpreting the data, and in subchapter 3.5 the results are interpreted. Subchapter 3.6 summarizes the chapter findings.

The results comprise three parts. First, the relevance of complexity drivers (SRQ 1) and the underlying structure of the complexity drivers (SRQ 2) are described, based on an explorative factor analysis. Second, the methods for mastering the complexity (SRQ 3), based on quantitative data generated in a survey, are presented. Third, the relationships between the methods along the value chain and the complexity drivers (SRQ 4.1) are outlined. Based on these relationships an ideal matrix for deriving methods is then proposed.

The survey results and statistical analyses of the complexity drivers and the methods for mastering complexity were already described in a publication by Kohr, Budde, & Friedli (*"Identifying Complexity Drivers in Discrete Manufacturing and Process Industry"* (Kohr et al., 2017)).

3.1 Survey design

To identify attributes from a larger population, the research team carried out a self-administered survey regarding "Global Complexity Management" on a comparably small group of individuals (Babbie, 2010; Fink, 2003). The research team sent out questionnaires cross-sectionally via email and postal mail. Each participant received either a print-out or an electronic version of the questionnaire accompanying the study. This data collection was done anonymously, therefore reducing the impact of bias towards social desirability, when compared to personal interviews (Bradburn, 1983).

The purpose of the survey was to identify the motivation of manufacturing companies towards implementing methods for mastering complexity. The research team included three main elements in the questionnaire:

- Which complexity drivers permitted a better understanding of the environment?

- Which possible targets along the value chain helped detect the strategic orientation?
- Which methods along the value chain helped to obtain insights into means and strategies applied within the manufacturing companies?

3.2 Population and sampling

The research team sampled by convenience, since mainly companies from Germany, Austria, and Switzerland were included due to their easy accessibility. To assure generalizability, companies from different industries were selected. To be suitable for the unit of analysis of identifying complexity management methods in a complex manufacturing context, the participants needed to fulfill several criteria. First, the companies needed to manufacture physical goods. Second, characteristics of complexity were controlled – e.g., number of employees, number of parts, type of production, and internationally dispersed value network.

To assure access to the necessary information, the research team contacted executives of the manufacturing companies via telephone or email. The executives often appointed a research coordinator to collect the data within the company. As the questionnaire requested accurate information on methods and performance numbers along the value chain, several functions needed to be consulted to assure reliability and validity. The sample characteristics are depicted in Table 10 and will be described below.

The industry sampled encompasses various sectors of the manufacturing industry. The majority of the sectors are engaged in mechanical/plant engineering (45.45%). The automotive, electronic, medical technology, and consumer goods industries account for most of the rest of the sample (32.58%).

Another classification of the sample was made using the number of employees. Most of the companies (76.7%) employ over 250 employees. Hence the main body of the sample is based on large companies. Regarding the products manufactured, the sample is dominated by companies offering assembly groups (consisting of approximately 100 parts) and machines (ca. 1,000 parts). The share of companies manufacturing heavy machines (ca. 10,000 parts) and components (ca. 1-10 parts) each constitutes about 17% of the sample. Furthermore, the sample is characterized by a type of manufacturing clustered in small-batch (29.5%), batch (36.4%) and mass production (21.2%), as well

as continuous production processes (12.9%). The degree of customer involvement, measured by the type of order fulfillment, also defines the complexity of the companies. The majority of the companies (58.3%) operate on a make to order (MTO) or assembly to order (ATO) basis.

Furthermore, the number of plant sites, the type of sites, and their locations show the degree of complexity of the value chain of the participating companies — the total sample operate at total 466 R&D, 1,042 production, and 4,519 sales sites. The majority of the companies owns sites in Western Europe, North America, Eastern Europe, and China.

Table 10: Characteristics of the final sample

Panel 1: Industry section		
Industry section	*Number of companies*	*Frequency*
Mechanical/Plant engineering	60	45.45%
Medical technology industry	9	6.82%
Consumer goods industry	8	6.06%
Electronic industry	9	6.82%
Aerospace engineering industry	1	0.76%
Optics and precision engineering industry	1	0.76%
Automotive industry	17	12.88%
Chemical indsutry	4	3.03%
Pharmaceutical industry	4	3.03%
Others	19	14.39%

Panel 2: Number of employees		
Number of employees	*Number of companies*	*Frequency*
< 50	5	3.8%
50 - 250	21	15.8%
250 - 1,000	34	25.6%
1,000 - 10,000	50	37.6%
> 10,000	18	13.5%

Panel 3: Products manufactured		
Kind of products	*Number of companies*	*Frequency*
Individual parts/components (1-10)	23	17.3%
Assembly groups (ca. 100 parts)	35	26.3%
Machines (ca. 1,000 parts)	39	29.3%
Heavy machines/plant engineering (ca. 10,000)	22	16.5%
Process industry goods	13	9.8%
Others	1	0.8%

Panel 4: Type of manufacturing		
Type of manufacturing	*Number of companies*	*Frequency*
Piece/small-batch production	39	29.5%
Batch production	48	36.4%
Mass production	28	21.2%
Continuous production processes	17	12.9%

Panel 5: Type of order fulfillment		
Type of order fulfillment	*Number of companies*	*Frequency*
Engineer to order	52	39.4%
Make to order/assemble to order	77	58.3%
Configure to order	48	36.4%
Make to stock	40	30.3%

Panel 6: Type of sites		
Type of site	*Number in total*	*Average number*
R&D	466	3.76
Production	1,042	8.61
Sales	4,519	38.30
Total	4,363	41.16

Panel 7: Global footprint of companies			
Area	*Number of companies with sites*		
	R&D	*Production*	*Sales*
North America	45	57	98
South America	13	35	73
Western Europe	102	103	113
Eastern Europe	46	65	82
Africa	5	15	56
India	24	34	76
Russia	6	17	70
China	38	65	95
Asia Pacific	5	11	68

3.3 Instrumentation

This subchapter provides information about the survey instrument used in the study. The questions of the survey regarding complexity drivers and methods were developed with a strong focus on pertinent literature (see also subchapters 2.4 and 2.6), as well as on insights from manufacturing companies obtained in interviews. First, the literature was examined thoroughly regarding theoretical constructs and relevant empirical studies (Sousa & Voss, 2008, p. 704). Through close collaboration with executives from nine manufacturing companies, the complexity drivers and methods[14] were condensed, along measures derived (Fowler, 2014, p. 95). Based on the feedback in the iterative adaptation cycles with executives, the constructs from the literature regarding the methods for mastering complexity were adapted.

The research team established measures for complexity drivers, target priority, and methods for mastering complexity. Based on these measures, the research team investigated the relationships between these complexity drivers and methods. Additionally, the research team investigated the relationships between the target priority and these methods. This subchapter outlines the development of the measurement models.

- First, the items used to measure complexity drivers of manufacturing companies are described.
- Second, the items of the target priority are detailed.
- Third, the methods for mastering complexity are delineated.

3.3.1 Complexity drivers

To measure the complexity drivers, the research team developed measurement models, since previous literature sources lack established measures for relevant factors along the value chain (Sousa & Voss, 2008, p. 705). For the development of the models for measuring the impact of complexity drivers, insights from literary sources, and from interview studies with researchers and practitioners, were combined (Sousa & Voss, 2008, p. 704). To assure content validity, the driver categories in the literature (compare subchapter 2.4) were tested with 16 company executives from nine manufacturing

[14] For further details see subchapter 2.6.

companies, and six research experts in the field of complexity management located in Germany, Austria and Switzerland (Dillman & Redline, 2004; Fowler, 2014, p. 103). The driver categories were adapted based on the feedback from practitioners. As a result of this refinement process, 19 complexity drivers were included in the final questionnaire. Table 11 lists the complexity driver categories and associated literature. The questions were examined in a one-item measurement. According to the approaches of Vickery et al. (1993), and Dean Jr. and Snell (1996) respondents were asked to rate the perceived influence of the drivers on the complexity in their company, on a five-point scale ranging from "very low (1)" to "very high (5)."

Table 11: Complexity drivers

Complexity driver	*Literature*
Legal factors	Ho (1996)
Political factors	Ho (1996); Pagell (2004)
Number of customers	Groessler (2006); Pagell (2004)
Variety of customer requirements	Raffi (1987); Groessler (2006); Anand (2004)
Volatility of customer demand	Droege (2003); Ho (1996); Calantone (2002)
Dynamics of competition	Jambulingam (2005); Calantone (2002)
Number of suppliers	Brandon-Jones (2015); Chen, I. J., & Paulraj, A. (2004)
Uncertainty of delivery (time)	Brandon-Jones (2015); Bhatnagar, R., & Sohal, A. S. (2005)
Uncertainty of delivery (quality)	Chen, I. J., & Paulraj, A. (2004)
Variety of products	Groessler (2006), Bliss (200); Giessmann (2010)
Dynamics of product portfolio	Groessler (2006), Bliss (200); Giessmann (2010)
Product structure	Giessmann (2010); Schoeneberg (2014)
Dynamics of product technology	Ho (1996), Droege (2003); Anand (2004); Bliss (200)
Degree of cross-linking of business processes	Schemenner (1985); Groessler (2006)
Number of value-added steps	Bayer (2010); Bliss (1998, 200); Keuper (2004)
Dynamics of production technology	Droege (2003); Anand (2004); Chen, I. J., & Paulraj, A. (2004)
Number of distribution levels	Nurcahya (2009); Bayer (2010)
Organizational structure	Bayer (2010); Blockus (2010); Collinson (2012); Kersten (2006)
Corporate culture	Brtolotti (2015); Adam (2012); James (2010)

3.3.2 Target priority

To measure the orientation of the complexity management of the participating companies, the research team consulted and analyzed the literature, and conducted

interviews. Based on the generic dimensions of competitive capabilities[15], the research team developed a list of targets for complexity management along the value chain, in close collaboration with 16 executives from nine manufacturing companies. Six researchers of the ITEM at the University of St. Gallen and the Laboratorium for Machine Tools (WZL) of the RWTH Aachen were involved in the development process, to assure content validity.

As a result, ten targets along the value chain of manufacturing companies were included in the questionnaire. The respondents were asked which of the targets are highly prioritized in their companies and were requested to evaluate them from "does not apply (1)" to "fully applies (5)."

- Reduction of product complexity
- Broader product program
- More innovative products
- Shorter time-to-market
- Reduction of production costs
- Reduction of process variety
- Production agility
- Order quantity flexibility
- Delivery time optimization
- Service optimization (after-sales/support)

3.3.3 Methods for mastering complexity along the value chain

Previous studies regarding the implementation of methods focused on individual parts of the value chain. The present research team built upon that work to develop measurement models for the entire value chain. The team included methods for mastering the market, production, and product complexity in manufacturing companies. For the development of the rating scales, the research team followed the approach of Hogan et al. (2011).

[15] Cost, quality, flexibility and delivery; also see J. S. Kim and Arnold (1996); Rosenzweig and Easton (2010).

As a result of the selection described in subchapter 2.6, the research team identified five methods, shown here in Table 12.

Table 12: Methods for mastering complexity

Methods	*Literature*
Modularity of products	Baldwin & Clark (1997), Göpfert (1998), Schaefer (2007)
Modularity of production processes	Feitzinger & Lee (1997), Schilling & Steensma (2001), Jacobs, Droge, Vickery & Calantone (2011)
Requirements engineering	Heumesser & Houdek (2003), Katina, Keating & Jaradat (2014)
Global management of modular product platforms	Dahmus, Gonzalez-Zugasti, & Otto (2001), M. Meyer et al. (1997), Chen & Liu (2005), Sanchez (1999)
Product portfolio management	M. A. Jacobs & Swink (2011), Rebentisch et al. (2016), R. G. Cooper (1999)

To assess the quality of quantitative research in business, reliability and validity are two important factors. Reliability evaluates the consistency of measures. Validity tests whether the measures of a construct really measure that construct. Even though reliability and validity are distinguishable, they are also mutually dependent. The validity of a measure can only be measured if reliability is assured. (Bryman & Bell, 2011, pp. 157–161)

In the following section, both the reliability and the validity of the measures will be described.

The reliability of measures indicates its consistency in reflecting a construct. It is tested through composite reliability (CR), which ranges from zero to one, whereby a level above 0.7 indicates a sufficient level of reliability. (Hair, 2010)

Three elements need to be included to test the validity of a measure:

- Content validity proves the apparent reflection of the content of the construct and can be established by interviewing people. This element is essential when new constructs are developed.

- Furthermore, the correlation of the items of a construct needs to be evaluated through convergent validity. It is tested by estimating the average variance extracted (AVE) for each construct. The threshold of 0.5 should be exceeded to achieve an appropriate level of convergent validity (Hair, 2010).
- Divergent validity tests the relatedness of different constructs in the measurement model. Cronbach's alpha values of the scales must exceed the interscale correlation estimates. Additionally, divergent validity is further supported by higher values regarding the between items to total correlation compared with the remaining scales. (Flynn et al., 1999, p. 262)

Six researchers from two research institutions in the field of complexity management were responsible on our research team for establishing content validity. The research team conducted a pre-test and discussed the results from the literature with executives from nine manufacturing companies located in Switzerland, Austria, and Germany. From 16 semi-structured interviews, the research team ensured content validity of the measurement items (Bryman & Bell, 2011, p. 160).

The interviewees worked in global functions – a process developer, a head of technology, a head of product architecture development, a head of product development, a manager in lean development, a manager in lifecycle processes, and an in-house consultant. In the interviews, the research team identified the relevance of the methods along the value chain. Furthermore, the interviews helped to validate and refine the measurement items.

The research team tested reliability and validity through statistical analysis, following the approach of Flynn et al. (1999). The methods for mastering complexity along the value chain were operationalized through multi-item indicators. Participants were asked to rate their agreement with various statements on a five-point scale from "does not apply (1)" to "fully applies (5)."

As shown in Table 13, the constructs are all above the 0.7 level of composite reliability and hence fulfill the reliability criteria. Convergent validity is assured through values for AVE above 0.5, except for product portfolio management (0.39). Evidence for divergent validity is provided through a comparison of alpha with interscale correlation values. This is further supported by a higher correlation within the scales, compared to the remaining scales. (Flynn et al., 1999; Lance et al., 2006)

Table 13: Reliability and validity of independent variables

Methods	AVE	CR	Cronbach's alpha	Average interscale correlation	Item/Toal correlation	
					Scale items	Non-scale items
Global management of product platforms	0.51	0.86	0.81	0.42	0.58	0.34
Modularity of products	0.66	0.86	0.79	0.56	0.64	0.32
Modular production processes	0.59	0.85	0.80	0.51	0.62	0.32
Product portfolio management	0.39	0.76	0.81	0.46	0.60	0.32
Requirements engineering	0.54	0.90	0.88	0.49	0.65	0.33

3.4 Data analysis and interpretation

Even though it is relatively rare (af Wahlberg & Poom, 2015), this research assured non-response bias based on the assumption that non-respondents behave similarly to late respondents (Lindner et al., 2001; Miller & Smith, 1983). The t-test showed that there is no significant difference between late and early respondents.

Data was also analyzed with three different methods to answer sub-research questions (SRQ) 1-4.

To answer SRQ 1, the averages for the complexity drivers in investigating the relevance of complexity drivers in the manufacturing industry was calculated. An explorative factor analysis (EFA) was conducted to identify the underlying structure of the complexity drivers. In four iterations the EFA derived the factors. In each step, based on the sample size of the research project of 130, factor loadings of greater than 0.5 are significant. Due to insignificant loadings, three complexity drivers were excluded to derive the final result. To answer SRQ 2, the results comprised six factors as the underlying structure of the complexity drivers. Furthermore, the averages via the measurement items for each method used for mastering complexity were calculated. The results from the reliability and validity tests supported the assumption that the underlying items reflected the overall constructs. Based on a correlation analysis, the relationship between methods for mastering complexity and complexity drivers in the manufacturing industry were investigated.

The author conducted the statistical analyses with IBM SPSS Statistics, version 25.

3.5 Results of the quantitative study

This subchapter describes the results of the statistical analysis. First, the complexity drivers and their importance in the manufacturing industry are outlined. Second, the underlying structure of the complexity drivers is elaborated. Third, methods for mastering complexity along the value chain are evaluated. Fourth, the analysis of the relationship of complexity drivers, as well as the strategic orientation of organizations towards the methods for mastering complexity, are detailed. Parts of these results were also described in the publication *"Identifying Complexity Drivers in Discrete Manufacturing and Process Industry"* (Kohr et al., 2017).

3.5.1 The relevance of complexity drivers

Based on the data of the survey, the research team investigated the importance of complexity drivers in the manufacturing industry. Table 14 summarizes the descriptive statistics of the complexity drivers. The individual drivers are sorted based on the mean value.

None of the 19 complexity drivers are rated as entirely irrelevant, indicating that the factors which increase the complexity are diverse. The three complexity drivers with the highest importance are: *variety of products, variety of customer requirements,* and *number of customers* with a mean value of 4.32, 4.28, and 3.92.

Several drivers, e.g., *degree of cross-linking of company processes, product structure* or *volatility of customer demand* have a medium-high influence on the complexity of manufacturing companies (mean between 3.25 and 3.45). With a mean value between 2.75 and 3.08 respondents rated the influence of *number of suppliers, number of value-added steps, dynamics of product technology,* and *uncertainty of delivery (time)*. The lowest importance was assigned to the drivers' *uncertainty of delivery (quality), number of distribution levels,* and *dynamics of production technology,* with mean values around 2.5.

Table 14: Descriptive statistics of complexity drivers

Complexity Driver	*N*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Variety of products	131	2.00	5.00	4.32	0.78
Variety of customer requirements	131	1.00	5.00	4.28	0.83
Number of customers	132	2.00	5.00	3.92	0.96
Degree of cross-linking processes	132	1.00	5.00	3.46	1.05
Product structure	131	1.00	5.00	3.45	0.98
Volatility of customer demand	132	1.00	5.00	3.42	1.08
Dynamics of competition	131	1.00	5.00	3.42	0.91
Dynamics of product portfolio	132	1.00	5.00	3.37	1.03
Legal factors	130	1.00	5.00	3.31	1.19
Organizational structure	132	1.00	5.00	3.29	1.07
Corporate culture	132	1.00	5.00	3.25	1.05
Number of suppliers	131	1.00	5.00	3.08	1.00
Value added steps	129	1.00	5.00	2.95	1.00
Dynamics of product technology	131	1.00	5.00	2.85	0.97
Uncertainty of delivery (time)	130	1.00	5.00	2.75	1.10
Political factors	132	1.00	5.00	2.58	1.17
Uncertainty of delivery (quality)	131	1.00	5.00	2.53	0.98
Number of distribution levels	130	1.00	5.00	2.45	0.97
Dynamics of production technology	131	1.00	5.00	2.38	0.89

3.5.2 The underlying structure of complexity drivers

Based on the data of the study, an exploratory factor analysis (EFA) was conducted to better understand the underlying structure of complexity drivers in the manufacturing industry. Sixteen of the nineteen variables (see also subchapter 3.3.1) were retained during the EFA. The sample size of 130 was adequate. The conceptual assumptions for a factor analysis regarding a set of variables, together with the characteristics and size of the sample, were fulfilled. Sufficient significant correlation in the data matrix was assured. (Hair, 2010, pp. 102–104)

In the analysis process, significant factors were established, and three variables were omitted due to insignificance. To identify the underlying structure of the variables a principal component analysis was applied. Based on the latent root criterion and the percentage of variance explained, the factors were derived from the variables. The derived factors were interpreted, and the final factor solution was selected based on the

conceptual foundation of the analysis. The factor matrix was rotated with the VARIMAX method to reduce ambiguities.

With an emphasis on practical significance, only factor loadings greater than 0.5 were included in the final factor solution. Based on the sample size of 130, factor loadings greater than 0.5 were considered statistically significant. In the process of EFA, the complexity drivers *crosslinking degree of company processes, product structure*, and *number of suppliers* were omitted due to insignificant factor loadings. (Hair, 2010, pp. 112–117)

Table 15: Results of explorative factor analysis (EFA)

	Factors underlying complexity drivers					
	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Complexity Drivers	*Production and value chain complexity*	*Product and market dynamics*	*Product and market variety*	*Supply uncertainty*	*Legal and political factors*	*Corporate structure and culture*
Number of distribution levels	0.77	0.05	-0.16	0.01	0.08	0.25
Dynamics of production technology	0.76	0.36	-0.02	0.13	0.13	-0.01
Number of value-added steps	0.76	-0.05	0.17	0.23	0.15	0.01
Dynamics of product portfolio	-0.11	0.77	0.08	-0.11	-0.01	0.22
Volatility of customer demand	0.16	0.70	0.09	0.29	0.03	0.05
Dynamics of product technology	0.36	0.65	0.14	-0.09	0.21	0.03
Dynamics of competition	0.06	0.52	0.21	0.28	0.26	-0.16
Variety of customer requirements	-0.10	0.24	0.79	0.12	-0.14	-0.08
Number of customers	0.24	0.10	0.78	-0.03	0.20	0.09
Variety of products	-0.10	0.04	0.63	0.12	-0.01	0.25
Uncertainty of delivery (time)	0.20	0.00	0.18	0.86	-0.02	0.08
Uncertainty of delivery (quality)	0.07	0.15	0.00	0.83	0.01	0.26
Legal factors	0.08	0.09	-0.02	0.00	0.84	0.18
Political factors	0.21	0.13	0.03	0.01	0.81	-0.10
Organizational structure	0.27	0.15	0.07	0.06	0.03	0.79
Corporate culture	-0.02	0.02	0.16	0.26	0.05	0.78

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 7 iterations.
Extracted: Number of suppliers; product structure; degree of cross-linking of company processes

An underlying structure consisting of six factors was identified during the EFA, as shown in Table 16. The factors were interpreted, based on a qualitative understanding, as *production and value chain complexity, product and market dynamics, product and market variety, supply uncertainty, legal and political factors,* and *corporate structure and culture.*

Table 16: Interpreted factors underlying complexity drivers

	Factors underlying complexity drivers					
	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Complexity Drivers	*Production and value chain complexity*	*Product and market dynamics*	*Product and market variety*	*Supply uncertainty*	*Legal and political factors*	*Corporate structure and culture*
Number of distribution levels	0.77					
Dynamics of production technology	0.76					
Number of value-added steps	0.76					
Dynamics of product portfolio		0.77				
Volatility of customer demand		0.70				
Dynamics of product technology		0.65				
Dynamics of competition		0.52				
Variety of customer requirements			0.79			
Number of customers			0.78			
Variety of products			0.63			
Uncertainty of delivery (time)				0.86		
Uncertainty of delivery (quality)				0.83		
Legal factors					0.84	
Political factors					0.81	
Organizational structure						0.79
Corporate culture						0.78

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 7 iterations.
Extracted: Number of suppliers; product structure; degree of cross-linking of company processes

The variance explained adds up to 68.727 % (24.572, 12.411, 1.558, 7.442, 7.358, 6.385).

Factor loadings on Factor 1 range between 0.757 and 0.769, on F2 between 0.522 and 0.769, on F3 between 0.634 and 0.794, on F4 between 0.831 and 0.856, on F5 between 0.814 and 0.843, and F6 between 0.782 and 0.795. All factor loadings are above the level of 0.5 and hence are practically and statistically significant. Cross-loadings of all variables are insignificant and substantially lower than the main factor loadings.

Factor 1 consists of items related to the structure of the value chain and the dynamics of production technologies. Results demonstrate that *number of distribution levels* is perceived as the highest complexity driver, followed by *number of distribution levels* and *dynamics of production technology*.

The items of Factor 2 describe the dynamism created by customers and competitors, as well as the product portfolio and technology. Hence, internal management practices regarding the product portfolio or technologies are interdependent with market characteristics. Especially *dynamics of competition, dynamics of product portfolio,* and

volatility of customer demand impact the complexity within manufacturing companies. In Factor 2 *dynamics of product technologies* has the lowest impact on the complexity (mean=2.847).

The variety of markets and products, represented by Factor 3, is ranked highest by respondents, with an overall mean of 4.173. With *variety of products* and *variety of customer requirements* this factor also entails the highest individual ranking among all complexity drivers (4.321 and 4.282). The correlation between *variety of products* and *customer requirements* is an indication of the development of the number of product variants in manufacturing companies with the increasing demand for individualization on the market.

Factors 4, 5, and 6 each consist of two external items. The items of Factor 4, with an overall mean of 2.644, describe the uncertainty of delivery relative to quality and time. Legal and political characteristics are covered by Factor 5 (overall mean = 2.946). Factor 6, with an overall mean of 3.269, encompasses the *organizational structure* and *corporate culture*.

A factor analysis on the set of complexity drivers was also conducted to understand the structure of relationships among the variables. In general, the derived factors and their importance are consistent with the current literature and fill a research gap of identifying contingencies in operations management (Sousa & Voss, 2008, p. 704).

3.5.3 Methods for mastering complexity

Based on the data of the survey, the implementation degree of the methods for mastering complexity along the value chain in the manufacturing industry was also investigated. Table 17 summarizes the descriptive statistics of the complexity drivers. The individual methods are sorted based on the mean value. None of the five methods were rated as completely irrelevant, which indicates that a set of methods needs to be applied to manage the complexity along the entire value chain.

The three methods with the highest implementation degree are *modularity of products, modular production processes,* and *requirements engineering* – with mean values of 3.15, 3.07 and 3.01. A lower implementation degree was investigated for the two methods *global management of modular product platforms* (mean value of 2.73), and *product portfolio management* (mean value of 2.26).

Table 17: Implementation degree of methods for mastering complexity

Methods	*N*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Modularity of products	131	1.00	5.00	3.15	1.06
Modular production processes	129	1.00	4.75	3.07	0.89
Requirements engineering	131	1.00	5.00	3.01	0.92
Global management of modular product platforms	131	1.00	5.00	2.72	0.99
Product portfolio management	131	1.00	4.60	2.26	0.89

The degree of implementation of the methods for mastering complexity seems to be relatively low. The author assumes this to be due to influencing factors which impede the implementation of methods along the value chain. The next subchapter investigates the links between complexity drivers, along with target priorities and methods for mastering complexity. (Sousa & Voss, 2008, p. 708)

3.5.4 Investigating the relationship of elements and the implementation degree of methods

In this subchapter the relationships between both elements, complexity drivers, and priorities on complexity management to methods for mastering complexity are investigated.

3.5.4.1 The relationship between complexity drivers and methods for mastering complexity

The analysis with respect to the relationship between the identified factors in subchapter 3.5.2 and the methods for mastering complexity resulted in no significant relationship. For this reason, and to get a better understanding of the relationship of drivers and methods, this subchapter conducts a correlation analysis on the individual driver level.

Table 18 shows the results of the correlation analysis. The relationship of the complexity drivers and the methods for mastering complexity are characterized by significantly low effects, since the values are smaller than 0.3 (Cohen, 1992).

The relationship between *legal factors* and *requirements engineering* has a low positive correlation, on a significance level of 0.05. A negative correlation of 0.276 (p=.01) was determined between *legal factors* and the degree of *modularity within products*. Hence, participants with a high relevance of legal factors tend to have a low degree of modularity of their products.

The *dynamics of product technologies* and the degree of *product portfolio management* correlate slightly positive (0.229) on a significance level of 0.01. Similarly, companies with high dynamism of product technologies also have a higher implementation degree of global management of modular product platforms, with a correlation of 0.193 on a significance level 0.05.

The implementation degree of *modular products* correlates negatively (-0.194; 0.05) with the *number of suppliers*. As a result of a modular product structure, the degree of shared components and parts increases. This leads to a lower number of suppliers overall. Therefore, the negative correlation is counterintuitive, but might be caused due to the circumstances of the individual company, e.g. if the number of suppliers cannot be reduced.

A negative correlation (-0.184; 0.05) can be seen between the *product structure* and the implementation degree of *requirements engineering*. Based on the description in subchapter 2.3, it seems counterintuitive since requirements engineering is important to manage diverse stakeholders. A highly complex product structure can induce an increase of stakeholders in the development process. Nevertheless, a high degree of complexity of the product structure also poses some challenges in implementing consistent requirements engineering. Especially the linking of requirements to product functions can be a challenge in a highly complex product structure.

Furthermore, significant negative correlations can be identified between the *uncertainty of delivery quality and time* and the implementation of *requirements engineering,* and the *global management of modular product platforms*. This correlation is not consistent with finding in the source literature.

Table 18: Correlation of complexity drivers and methods

Complexity Drivers	*Methods for mastering complexity*				
	Product portfolio management	*Requirements engineering*	*Global modular product platforms*	*Modularity of products*	*Modular production processes*
Legal factors	0.099	0.179*	0.011	-0.276**	-0.082
Number of suppliers	0.040	-0.075	0.050	-0.194*	-0.065
Uncertainty of delivery (time)	-0.123	-0.298**	-0.206*	-0.042	-0.023
Uncertainty of delivery (quality)	-0.023	-0.195*	-0.038	-0.004	0.072
Product structure	-0.052	-0.184*	-0.031	0.043	-0.034
Dynamics of product technology	0.229**	0.070	0.193*	0.006	-0.087

** Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)*

Comparing these results with those from the literature review yields the conclusion that only minor overlapping can be identified. Similar to findings in the literature, the quantitative analysis identified a significant relationship between *product portfolio management* and *dynamics of product technology*. In both results, the statistical analysis and the literature review, *global management of modular product platforms* is related to the *dynamics of product technology*. With regards to *requirement engineering* and *modularity in products* and *processes*, the statistical analysis revealed no results overlapping with those in the literature.

Based on the correlation analysis between the complexity drivers and the methods for mastering complexity, an idealized matrix for deriving methods will now be described.

The matrix indicates a tendency of manufacturing companies towards methods based on their complexity drivers (see Table 19). On the one hand, the low negative correlation between the complexity driver *legal factors* and the method *modularity of products* shows a tendency of manufacturing companies to refuse to implement this method. On the other hand, *requirements engineering* is positively correlated with *legal factors,* which indicates a preference to implement this method for mastering the complexity created by regulations, for example.

The complexity driver *number of suppliers* is negatively correlated with *modularity of products,* indicating that a company would refuse to apply modular products in the face

of a high number of suppliers. Manufacturing companies confronted with *a high uncertainty of delivery (time)* tend towards not applying the methods *requirements engineering* and *global modular product platforms.*

With a high *uncertainty of delivery (quality),* manufacturing companies also indicate a tendency towards a lower degree of *requirements engineering*. The complexity driver *product structure* is negatively correlated with the method *requirements engineering*. Manufacturing companies facing high dynamism of product technology show a significantly higher implementation degree of the methods *product portfolio management* and *global modular product platforms*.

Table 19: Relationships between complexity drivers and methods for mastering complexity

	Methods				
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*
Variety of products			•	•	
Variety of customer requirements	•	•	•	•	•
Number of customers		•	•		
Volatility of customer demand	•	•			•
Dynamics of competition	•				
Dynamics of product portfolio			•	•	
Organizational structure		•			
Dynamics of product technology	•/+	•	•/+	•	
Political factors					•
Dynamics of production technology			•	•/+	+
Legal factors		+		-	
Number of suppliers				-	
Uncertainty of delivery (time)		-	-		
Uncertainty of delivery (quality)		-			
Product structure		-			

• relationship identified from the literature
+/- relationship identified from the study

3.5.4.2 The relationship between priorities of complexity management and methods for mastering complexity

The correlation analysis between priorities of the complexity management of manufacturing companies and the methods for mastering complexity indicates in several weak significant relationships.

Companies with a high priority on *broader product programs* tend to implement *product portfolio management, requirements engineering, global management of modular product platforms* and *modularity in products*. With r-values of 0.296 and 0.266 on a significance level of 0.01, the correlation towards *requirements engineering* and *global management of modular product platforms* is the strongest. The correlations towards *product portfolio management* (0.23) and *modularity of products* (0.185) are significant on a level of 0.05.

This result is consistent with the literature, as the implementation of a consistent product portfolio management helps to efficiently increase the product program. Furthermore, implementing *requirements engineering* helps to identify the needs of the customers and white spots in the product portfolio. Through *modularity of products* and *global management of modular product platforms*, a broad product program can be implemented more efficiently.

A high priority among participants for *reducing the production costs* is significantly correlated with the implementation degree of *product portfolio management* (r=0.251, p=.01) and *requirements engineering* (r=0.217, p=.05).

Based on the literature, methods regarding modular process technology would have been expected to have a higher significant correlation with the priority of reducing production costs. Nevertheless, this results can be explained based on secondary effects. Managing the product portfolio of a manufacturing company leads to a lean product offering and therefore reduces the variants in the production. The complexity in the production can therefore be reduced, which helps to lower the costs. In the same way, a high implementation of requirements engineering can help to improve the product offering and therefore reduce the variants produced.

The goal of reducing *process variety* is significantly correlated with *product portfolio management* (r=0.216) and *global management of modular platforms* (0.181), on a significance level of 0.05.

Similar to the description above, the implementation of product portfolio management helps to maintain a lean product offering and therefore helps to prohibit an increase of process variety. The global management of modular product platforms also supports standardizing tools and the means of production used in the processes across product variants.

Furthermore, a significant correlation of 0.183 was identified between the *priority of increasing the order quantity flexibility* and *requirements engineering,* on a significance level of 0.05. With a maximum explained variance of 9% (r^2) the results of the correlation analysis do not support further statistically investigating these relationships.

Table 20: Correlation of priorities of complexity management and methods

Priorities	*Methods for mastering complexity*				
	Product portfolio management	*Requirements engineering*	*Global modular product platforms*	*Modularity of products*	*Modular production processes*
Reduction of product complexity	0.035	0.080	0.065	0.108	-0.050
Broader product program	0.230*	0.296**	0.266**	0.185*	-0.034
More innovative products	0.156	0.214*	0.093	0.101	0.145
Shorter time-to-market	0.100	0.174	0.003	0.122	-0.061
Reduction of production costs	0.251**	0.217*	0.100	0.155	-0.043
Reduction of process variety	0.216*	0.131	0.181*	0.040	-0.035
Production agility	0.083	0.031	0.090	-0.091	-0.017
Order quantity flexibility	0.169	0.183*	0.138	0.040	0.177
Delivery time optimization	0.122	0.061	0.035	-0.005	0.040
Service optimization	0.120	0.024	0.131	0.075	-0.005

** Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)*

3.6 Conclusion

Based on the results of this analysis, it can be concluded that complexity drivers only slightly interrelate with the applied methods for mastering complexity within our sample of manufacturing companies. These results indicate that these manufacturing companies do not identify their methods based solely on the manifestation of their complexity drivers. Some of the significant correlations are not in line with the literature and therefore cannot be explained based on the descriptions in subchapters 2.3 and 2.6.

Therefore, Chapter 4 will further investigate the processes of identifying and conceptualizing methods, using case information from five companies in the manufacturing industry.

Based on the results of the quantitative study, this chapter derived adaptations of the relationship matrix from subchapter 2.6.4. The relationships between the complexity drivers and the methods showed significant positive and negative correlations. Combining insights from the literature analysis and the quantitative study, an idealistic relationship matrix was presented for identifying methods based on the complexity drivers at manufacturing companies (see Table 21).

Table 21: Idealized matrix for deriving methods based on complexity drivers

	Methods				
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*
Variety of products			•	•	
Variety of customer requirements	•	•	•	•	•
Number of customers		•	•		
Volatility of customer demand	•	•			•
Dynamics of competition	•				
Dynamics of product portfolio			•	•	
Organizational structure		•			
Dynamics of product technology	•/+	•	•/+	•	
Political factors					•
Dynamics of production technology			•	•/+	+
Legal factors		+		-	
Number of suppliers				-	
Uncertainty of delivery (time)		-	-		
Uncertainty of delivery (quality)		-			
Product structure		-			

• relationship identified from the literature
+/- relationship identified from the study

4 Case study research

The following chapter analyses the influencing factors for identifying and conceptualizing methods for mastering complexity based on case study research with five companies from the manufacturing industry. Its primary aim is to provide answers to sub-research question (SRQ) 4.

The chapter is organized into seven subchapters. Subchapter 4.1 describes the case study methodology. In subchapter 4.2, the process of selecting the cases and the individual characteristics of the case companies are detailed. Subchapter 4.3 focuses on the sources and the manner of data collection. The methods within and across the cases are analyzed in subchapter 4.4. The topic of reliability and validity is outlined in subchapter 4.5.

Subchapters 4.6 and 4.7 describe the findings of the within-case and cross-case analyses along various dimensions. The within-case analysis focuses on the methods applied by the case companies and these methods' relationships to the complexity drivers at the case companies. Furthermore, the processes of identifying and conceptualizing methods for mastering complexity at the case companies are elaborated on. The next subchapter, with the cross-case analysis, summarizes the relationships between complexity drivers and methods for mastering complexity and additional common influencing factors across the five cases, to answer SRQ 4. The relationship of the methods to the complexity drivers is analyzed and compared with the relationship matrix drawn from the literature and the quantitative study, helping to answer SRQ 4.1. The identified influencing factors for identifying and conceptualizing methods for mastering complexity support answering SRQ 4.2.

A comparison is made between the identified interdependency matrix in subchapter 3.6 and the insights from the cases in the conclusion of this chapter (4.8).

4.1 Case study methodology

The findings of the quantitative approach and the literature motivated the author of this dissertation to conduct exploratory research regarding influencing factors in the manufacturing industry, with the aim of identifying and conceptualizing methods for mastering complexity. This dissertation applies case study research methodologies suitable for topics with limited knowledge about issues and variables. It also helps to explain a particular phenomenon, outlined by Voss et al. (2002), namely that "field-

based research methods" are in high demand among operations management researchers "to cope with the growing frequency and magnitude of changes in technology and managerial methods" (Voss et al., 2002, p. 195). Based on single individual case observations, an inductively derived, generalizable theory is presented in this subchapter. According to Yin (2003, p. 5), case study research is most appropriate for research questions starting with "how", "why", and "what." Our present research study applies case study research to answer SRQ 4.1 and SRQ 4.2, to find influencing factors for identifying and conceptualizing methods for mastering complexity.

4.2 Case selection

Based on theoretical sampling, five multinational companies – from the automation, pharmaceutical, mechanical engineering, and automotive industries – were selected (Eisenhardt & Graebner, 2007, p. 27). The case companies had either recently implemented or were in the process of identifying and conceptualizing methods for mastering complexity. The present author chose a multiple case study approach to investigate different contexts consistently. The multiple case study approach also allows for a higher degree of generalizability of the outcomes, as the methods of the case companies aim to master complexity in various stages of the value chain. The characteristics of the selected case companies and position of the informants, as well as the methods used, are shown in Table 22.

The case companies differ from the companies involved in the funnel model in subchapter 2.6.2 and therefore the selection of methods for mastering complexity is different. This demonstrates even more that the application of methods for mastering complexity is dependent on the individual company and many influencing factors. At the end of Chapter 4, the reader will have deeper knowledge about some of these factors.

Table 22: Overview of cases

Case	Position of informants	Employees	Methods
BA	Head of Development Actuators Division Head of Development Department Head of Data Management Division Senior Development Engineer Head of Development Mechanics	> 1,000	Technology Super Market, Modular product structure
PC	Head of Process and Knowledge Management Director Business Continuity & Process Management Process & Knowledge Manager	> 120,000	Process-oriented Standard Operating Procedures (PO-SOP)
AC	Head of Complexity Management	> 80,000	Holistic complexity management approach
FC	Head of Complexity Management Complexity Manager	> 6,000	Modular product structure, standardization of assemblies, preferred series, reuse of parts search, variant configurator
AI	Method Consultant	> 120,000	Standardization of production, requirements engineering

AC: Automotive Company; AI: Automotive, Inc.; BA: Building Automation; FC: Forming Company; PC: Pharmaceutical Company

4.3 Data collection

The data related to the process of identifying and conceptualizing methods for mastering complexity in these manufacturing companies were collected based on various data sources. This present research includes group and individual interviews, archival data, and on-site observations. Based on projects during 16 respectively 18 months with Building Automation, Inc. and Pharmaceutical Company, the author gained detailed insights through his on-site observations. The author was given access to the Forming Company by participating in a focus group. In three meetings, the company's approach regarding the derivation of methods for mastering complexity was discussed, and the circumstances on-site were observed.

In a benchmarking study, Automotive Company had been awarded as Successful Practice Company. The author was fortunate to get the chance to discuss the company's approach towards mastering complexity, with various involved employees on-site. Automotive, Inc. had participated in past projects and a benchmarking study. The author conducted additional interviews with all case companies, based on semi-structured interview guidelines.

In the sense of triangulation of data (Eisenhardt & Graebner, 2007, p. 28), archival data and survey data, along with the interviews, on-site observations and industry projects, will be analyzed in this subchapter.

Table 23: Overview of meetings with case companies and total duration

Case	Number of meetings/interviews	Duration [h]
BA	15	30
PC	32	77
AC	3	18
FC	4	35
AI	3	4

AC: Automotive Company; AI: Automotive Inc.; BA: Building Automation; FC: Forming Company; PC: Pharmaceutical Company

4.4 Data analysis

First, a within-case analysis of each case company was conducted. The author created write-ups for each case and analyzed the patterns individually. Second, the author searched for cross-case patterns regarding similarities and differences among various dimensions. The individual case companies identified and conceptualized methods in various stages along the value chain. (Eisenhardt, 1989, pp. 539–540)

4.5 Reliability and validity

Construct validity determined whether the correct operational measures for concepts being studied had been established (Judd et al., 1991, pp. 27–29). In the data collection process, this present dissertation applied two approaches to assure construct validity. For triangulation of data, the author investigated multiple sources of evidence (e.g.,

interviews, company presentations, group interviews). The drafts of the case study reports were reviewed by the key informants (Yin, 2003, p. 34). The feedback helped to deepen the insights into the individual cases and validate the information.

External validity deals with the issue of generalizing the case study results. The reliability of a case study describes the degree of a case study to be replicated (Yin, 2003, p. 34). The research design of this present study assured generalizability based on the replication logic. In five case studies, this research investigated the process of identifying and conceptualizing methods for mastering complexity. To assure the reliability of the findings, the procedures of the case studies were documented, after a case study protocol and a case study database had been developed.

4.6 Within-case analysis

Within-case analysis was the first step towards analyzing the data, "the heart of building theory from cases" (Eisenhardt, 1989, pp. 539–540). Eisenhardt emphasizes the importance of within-case analysis with the overall idea "to become intimately familiar with each case as a stand-alone entity." By means of within-case analysis the author was able to cope with the immense amount of data. Each case develops its individual patterns before the researcher identifies generalized patterns across the cases.

The five individual cases will now be described in more detail. The case-companies applied a variety of methods to influence different stages along the value chain.

- First, the individual cases will be analyzed regarding their decisions to adopt methods for mastering complexity, and the relationship of these methods to the complexity drivers.
- Second, an analysis will follow the similarities and differences between the relationships of methods and complexity drivers identified in the literature, the quantitative studies, and the case studies.

4.6.1 Case I – Building Automation, Inc. (BA)

Building Automation, Inc. was founded in 1975, and specializes in consulting, delivery, and installation of actuators for heating, ventilation, and air-conditioning purposes. In the early years, the company set up independent sales subsidiaries in England, Finland, Norway, Austria, Denmark, France, Sweden, and Holland. The expansion continued

with a facility in the USA in 1988. Today, BA is the global market leader and operates facilities in more than 80 countries. BA focuses its efforts on the development and the delivery of its solutions. The production of all components is outsourced to suppliers. Therefore, the management of the supply chain is a key lever for BA to be competitive. Currently, about 1,500 employees generate a global sales volume of about 580 million Swiss francs. BA offers solutions in wide-ranging fields, and its core business consists of actuators, valves, and sensors, as well as systems for optimizing energy efficiency. The company assembles about six million actuators per year.

During the author's activities as a research associate at the Institute of Technology Management (ITEM), BA participated in a benchmarking study in the field of "global complexity management", and also consulted the ITEM in a project to conceptualize a method to support the development of its products. In the benchmarking project, the research team identified complexity drivers, as well as methods and structures in the manufacturing industry for mastering complexity. They received data which helped to determine the relevance of individual drivers along BA's value chain. Furthermore, the research team was able to identify the implementation degree of methods for mastering market, product, and production and supply chain complexity.

In close collaboration with the development team of the actuator division, the ITEM conducted a project to conceptualize a method to increase the efficiency and effectiveness of product development through a 'Technology Super Market (TSM)'. Based on interviews, the author obtained insights into the process of identifying and conceptualizing the modular product structure (MPS) and its impact on the processes. These insights are presented in the following section.

4.6.1.1 Description of MPS and TSM

To cope with increasing complexity, BA has introduced several innovative methods in the past. MPS[16] and the TSM will now be described, with particular reference to the complexity drivers used.

[16] Subchapter 2.6.3.2 further elaborates on the concept of modularity of products.

Modular Product Structure (MPS)

Individual customer demands have increased the product variety within BA. Before implementing the MPS, engineers developed each product variant individually, which led to redundant components with similar functions. The many different sizes and materials increased the problems and resulted in greater strains in the assembly processes, due to the many changes regarding tools and equipment. To strengthen the structure within the product portfolio and its consisting components, BA introduced the MPS. Implementing the MPS affected the development of products, as well as the production and supply chain processes within the company. BA was able to increase the number of offered product variants while at the same time reducing the number of components and the difficulties in the development and production processes. As a result, the sales employees were able to offer customers more flexibility in choosing products suitable for the applications. By increasing the degree of shared components across all product lines, BA achieved economies of scale and scope and therefore reduced the costs per product. Furthermore, BA achieved a higher level of standardization of production processes across all product lines, thus allowing for significant investments in production technologies, like automatization.

The degree of shared components across the entire product portfolio increased up to 90% for individual components. A failure in one of these components would cause great difficulties in identifying and repairing all the affected products. Thus, BA implemented a structured process to coordinate innovations across the entire product structure. Therefore, the development team planned product changes with more time ahead and evaluated, in exchanges with stakeholders, its effects on the entire value chain and product portfolio.

The product structure, characterized by its independent modules, enabled the implementation of more innovations. BA was able to innovate individual modules independently from other modules, which led to more flexibility and faster product development.

Along with the MPS, BA adapted its value chain processes. The entire production process was divided into two stages – customer-neutral prefabrication of assemblies, and finalization of individual customer products. The two stages were assigned to plants with separate roles. The main plant in Switzerland, which is also the global headquarters, performed the pre-fabrication. Customizing plants in seven other worldwide locations contributed the mechanical and electronic interfaces, cables and parametrizing, along

with labeling, to serve individual customer demands. BA operates according to “Make to Order” (MTO) / “Assembly to Order” (ATO) order procedures. Through implementing modular product structures, BA has managed to decrease the time period from customer order to delivery.

Based on the modular product structure, including standardized interfaces, BA has achieved a higher degree of standardization and automation within its production. Additionally, the cooperation with suppliers regarding the development of modules was intensified. During the implementation period, BA developed the modules in cooperation with suppliers. Later on, BA focused on its strengths and outsourced the production of parts of the final product. Suppliers innovated their assembly processes and achieved a fully automatized assembly of individual modules.

Technology Super Market (TSM)

BA, especially in its development department, today faces difficulties in keeping an overview of all components and their relationships. The main reasons for this are to be found in the high number of active components, along with a certain non-transparency regarding their differences and combinability. The TSM incorporates all of the components, including the detailed knowledge of their characteristics and relationships to one another, and can be described as an internal product configurator. An intelligent search algorithm supports the developers in configuring customer products by finding suitable components. In case no suitable component for the individual customer request exists, the TSM shows how to adapt to them with slightly deviating components. The main aims of this method are to predict the time and feasibility of development projects more accurately, and to reduce the number of iterations and overall expenditure of time.

The TSM affects all phases of the development process, from idea generation to the start of assembly. The combination of the components creating the actuators is based on the tacit, internal knowledge of the employees. Currently, to fulfill a customer order, this tacit knowledge needs to be made available by interviewing different people within the company. The TSM integrates this tacit knowledge, leading to an increase in efficiency and effectiveness of the processes, for example the dimensioning of an actuator. With the use of the TSM, the number of sudden and unforeseen events (for example, a mismatch of components) in the development phases is minimized. As a result, the development process is more stable and faster. Furthermore, the informant expects that

the TSM will affect the quality of the components, since inconsistencies will become instantly apparent.

Table 24 summarizes the relationships of the complexity drivers and the methods for mastering complexity implemented at BA. Furthermore, the table enables a comparison of the differences and similarities between BA and the relationships derived from the literature and the quantitative study.

The implementation of MPS at BA is related to the three complexity drivers *variety of customer requirements, variety of products* and *number of products.* Therefore, the relationship of variety of customer requirements and variety of products to modularity of products reflects findings in the literature. Some complexity drivers, identified as relevant in the literature and the quantitative study, did not influence BA to implement MPS.

Dynamics of production technology was identified in the literature and in the correlation analysis of the quantitative study to be related to *modularity of products*. In the quantitative study a positive correlation was identified; therefore, a high influence of *dynamics of production technology* resulted in a high implementation degree of the method *modularity of products*. In the relevant literature a relationship between d*ynamics of product technology* and *dynamics of product portfolio* is given emphasis. Furthermore, a significant negative correlation between *modularity of products* and *legal factors,* as well as *number of suppliers,* was identified in the quantitative study. These complexity drivers did not influence BA to implement MPS.

The method *TSM* was not identified in the literature research as a key method for mastering complexity, and as a result was not included in our quantitative study. Therefore, a comparison between quantitative study, literature and BA regarding this method has not been made. Table 24 visualizes the identified relationships of TSM and complexity drivers.

Table 24: Relationship of complexity drivers and methods at BA

	Methods						
	Literature and quantitative study					*BA*	
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	Modular Product Structure (MPS)	Technology Super Market (TSM)
Dynamics of production technology			•	• /+	+		
Volatility of customer demand	•	•			•		
Dynamics of product technology	• /+	•	• /+	•			
Dynamics of product portfolio			•	•			•
Dynamics of competition	•						
Variety of customer requirements	•	•	•	•	•	•	•
Variety of products			•	•		•	•
Number of customers		•	•				•
Uncertainty of delivery (time)		-	-				
Uncertainty of delivery (quality)		-					
Political factors					•		
Legal factors		+		-			•
Organizational structure		•					
Corporate culture							
Number of suppliers				-			
Product structure		-					•
Number of products						•	•
Variety of production & SC processes							

• Relationship identified in the literature & cases

+/- Significant correlation identified in the quantitative study

4.6.1.2 The process of identifying and conceptualizing MPS and TSM

BA introduced the MPS and the TSM for mastering the complexity within the organization. The process of identifying and conceptualizing the two methods will now be described.

Modular Product Structure (MPS)

First, BA analyzed the complexity drivers within the organization. The number of different customer requirements and the number of product variants indicated an increase of complexity within the organization. As a result, BA identified the product structure as being one of the main levers and decided to implement the MPS across all product lines. Second, BA created a team to conceptualize the modular structure of the products.[17] The MPT consisted of employees from the development department – specialized in mechanics, electronics and software – as well as from the production department. MPT also cooperated with suppliers to conceptualize the MPS. Third, the MPT analyzed the current product structure and identified actions to implement modularity across the entire product portfolio. Fourth, the MPT defined mechanical and electrical interfaces to connect the individual modules. Fifth, in close collaboration with the business units and the product portfolio management, the MPT defined modularity targets to control its adherence to guidelines. Sixth, BA dissolved the MPT, and their members were integrated into the initial organizational structure.

Technology Super Market (TSM)

In over 40 business years, the numbers of product variants, components, technologies, as well as supply chain and internal processes have increased within BA. The ITEM conducted a project with BA aiming to identify needs and conceptualize a method to support the developers in transferring customer orders into final products. The research team investigated whether a "Technology Super Market" (TSM) can be a useful tool for supporting the various stakeholders in increasing the speed in product development in the actuators division. The overall project consisted of five stages, as depicted in Figure 18.

[17] The interdisciplinary, dedicated team for implementing modular products will be referred to as "Modular Products Team (MPT)."

First, the research team conceptualized the TSM. In interdisciplinary workshops, with employees from different divisions, the research team identified structures and purposes. As a result, the research team created use cases, workflows, then defined tasks and responsibilities within the TSM.

Second, the research team identified all relevant components and modules, and the necessary information about them. In this stage, the research team built up an understanding of the product structure, including the components and modules, as well as their functions and their relationships.

Third, the research team described all components and modules with pertinent information. This characterization set formed the basis for determining the relationship knowledge in the next step.

Fourth, to gain knowledge about the relationships, the individual divisions prepared a combination matrix with all dependencies. In an interdisciplinary workshop with stakeholders from all divisions, the research team identified inconsistencies regarding the relationships. As a result, the different divisions needed to work together to establish a consistent description of the relationships of all components.

Fifth, based on the final description of the relationships, the research team implemented the TSM prototype. The prototype helped to visualize the various combination possibilities of all components necessary to create a final product. The search algorithm considered all relationships and characteristics required by the user. To test the applicability and the advantage, the research team conducted interviews and an interdisciplinary workshop.

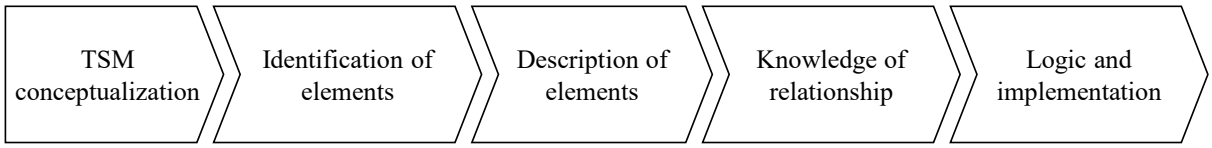


Figure 18: TSM project stages

4.6.2 Case II – Pharmaceutical Company (PC)

Pharmaceutical Company is a research-based pharmaceutical company offering a wide range of medications. It operates within a wide-ranging global manufacturing network, at around 50 sites. The management of the product portfolio, along with the production and supply chain processes, provide key leverage for PC's competitiveness. Currently, about 100,000 employees generate a global sales volume of more than 30 billion euros.

During the author's time as a research associate at the ITEM, PC consulted them in a project to conceptualize a method to support the management of SOPs (Standard Operating Procedures). In close collaboration with the corporate quality team, the research team identified the efforts along the SOP creation process and conceptualized an innovative process-oriented SOP (PO-SOP) architecture. Additionally, PC participated in the benchmarking project regarding "Global Complexity Management" (described in Chapter 3).

4.6.2.1 Description of PO-SOP

In the highly regulated pharmaceutical industry, a company's processes and products are certified by local authorities. To allow the employees to perform their tasks consistently, SOPs describe the processes in detail. As a result, a minimum number of process variants and an increased level of standardization of execution are achieved.

Currently, PC's corporate quality department perceives a high complexity within their SOP management processes. An increasing number and variety of SOPs creates non-transparency, which in turn causes great hindrances in creation and reviewing processes. PC faces challenges in creating SOPs and evaluating the impacts of regulatory changes. Informants state that the high number of SOPs, as well as missing standards of structures and styles, cause and aggravate these challenges.

Creating SOPs involves many interdisciplinary employees with experience in selected fields of the value chain and the product portfolio. Since the number of SOPs results in a lack of transparency, evaluating the impacts of regulatory changes generates considerable obstacles. The content within the SOPs is partly redundant, which also results in higher maintenance outlays.

The current efforts in the SOP creation process add up to about 12.5 full-time employees (FTEs). This is mainly influenced by the number of affected product categories, as well as the participation of diverse functions and the number of people in the SOP process. The process consists of twelve process steps from 'analysis of impact' of external regulatory bodies to the 'implementation support' for the sites. The process steps 'authoring', 'confirmation of receipt', and 'implementation support' account for the most significant effort in the process.

As a reaction to this, PC decided to innovate its SOP architecture. PO-SOP architecture is defined by standardized contents and structure and utilizes modular components.

Through process orientation, the time and efforts needed in creating and reviewing are decreased. Furthermore, since the adapted SOP architecture is designed intuitively, users do not need to be trained to work with SOPs. The informant expects an increase in efficiency and effectiveness regarding the evaluation processes of the impact of regulatory changes on PC's SOPs. The effort along the whole creation process is expected to be reduced by 30% (9.1 FTE). Furthermore, the informant expects an increase in robustness of the process of SOP implementation.

PO-SOP also affects PC's organizational structure. As a reaction to the results of this project, the internal structure of the PKM department was adapted. Similar to the structure of the SOP creation process, the PKM department now consists of twelve teams responsible for the individual steps of the SOP creation process. In order to increase the efficiency within the corporate quality department, the informant expects a structural change in the near future.

Through PO-SOP the work of the SOP managers will change. While the SOP manager is currently considered a document manager, his tasks will shift towards process management duties, and the necessary future skills for this position will change. Furthermore, the process orientation aids in uncovering waste and inefficiencies in the organization. Therefore, the informant expects a cultural change towards operational excellence within the organization. The PO-SOP affects the whole organization and helps it to be compliant throughout all processes.

Table 25 visualizes the relationship of complexity drivers to the method PO-SOP at PC. PO-SOP was not identified in this author's literature review as a key method for mastering complexity, and as a result was not included in the quantitative study. Therefore, a comparison between quantitative study, literature, and PC will not be drawn.

Table 25: Relationship of complexity drivers and methods at PC

	Methods					
	Literature and quantitative study					*PC*
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	Process-oriented SOP
Dynamics of production technology			•	• /+	+	•
Volatility of customer demand	•	•			•	
Dynamics of product technology	• /+	•	• /+	•		•
Dynamics of product portfolio			•	•		
Dynamics of competition	•					
Variety of customer requirements	•	•	•	•	•	•
Variety of products			•	•		•
Number of customers		•	•			
Uncertainty of delivery (time)		-	-			
Uncertainty of delivery (quality)		-				
Political factors					•	•
Legal factors		+		-		•
Organizational structure		•				
Corporate culture						
Number of suppliers				-		
Product structure		-				
Number of products						•
Variety of production & SC processes						

• Relationship identified in the literature & cases

+/- Significant correlation identified in the quantitative study

4.6.2.2 The process of identifying and conceptualizing PO-SOP

The ITEM supported PC in the project, helping to identify and conceptualize the method PO-SOP. The overall project consisted of six stages, as shown in Figure 19. First, the research team gathered knowledge for the current SOP system. In workshops with executives from the process and knowledge management (PKM) team, the research team identified the structure, the content, and the creation process of SOPs. The SOP creation process consists of activities on corporate and site level. SOP managers on corporate level identify the impacts of regulatory changes on the Global SOP landscape of PC. As a result, adapted Global SOPs are communicated to the sites. Quality executives at the sites are responsible for adapting their SOPs according to the changes on the corporate level. Therefore, since the process of managing SOPs involves employees from corporate and site levels, the research team included both perspectives to identify the efforts within the current entire SOP process.

Second, the research team developed a questionnaire to measure the efforts by semi-structured interviews. In collaboration with the PKM team, the research team defined questions regarding the process steps and their efforts, number of SOPs, challenges in the process, as well as improvement potentials.

Third, to collect the data, the research team conducted interviews in person and via telephone on a corporate level with executives in the quality department of five sites in Germany. The author and a member of the PKM team conducted the interviews together to clarify the scope and aim of the project within PC.

Fourth, the research team analyzed the data to develop the model for evaluating the efforts in the SOP processes. The result, an evaluation model, visualized the efforts along the creation process of SOPs and assigned it to the various stakeholders involved. Furthermore, the research team assigned complexity drivers to the individual process steps. Thanks to its adaptive character, the evaluation model provided support in creating different scenarios.

Fifth, based on effort estimations by executives from the PKM team, the research team was able to create a scenario for the future SOP architecture. A comparison of the current and future efforts indicated the potential of implementing this method. In the last and sixth step of the project, the research team derived implications for the future SOP process.

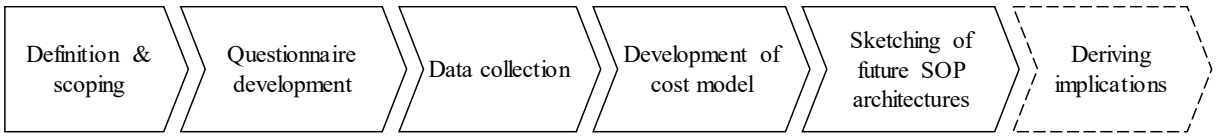


Figure 19: SOP complexity project stages

4.6.3 Case III – Automotive Company (AC)

Founded in the early 20th century, Automotive Company (AC) develops and manufactures complex products for the automotive sector. AC offers a wide-ranging product portfolio to an international customer base in more than 100 markets. Through a global production network consisting of fifteen sites, AC produces about two million products yearly. In recent years, AC has achieved high growth rates, resulting in a 300% increase in the number of product variants; this has led to creating a workforce of more than 90,000 employees worldwide. Individual customer demand and the dynamics of product and production technologies contribute to a high complexity along AC's entire value chain, so that the company has conceptualized a method for mastering this complexity from a holistic perspective.

4.6.3.1 Description of HCM

AC has invested in complexity management for about 20 years. Mainly driven by individual employees, it long retained an isolated approach in the development department. Since the effects on the subsequent processes of the value chain were not considered thoroughly enough, negative implications had to be managed in addition to the individual approaches. For example, a change in the product structure can lead to non-manufacturability of products, which results in post-adaptations of the product structure and therefore leads to reworking associated with higher costs along the entire value chain.

The method "Holistic Complexity Management" (HCM[18]) aims at anchoring the sense of complexity within the whole organization.[19] HCM considers and aligns requirements related to the complexity of AC's departments and employees parallel to identifying

[18] In the following section the method for holistically managing complexity will be referred to with the abbreviation "HCM."

[19] The HCM at AC can be understood as a combination of methods for mastering the complexity along the value chain. For a further description of methods for mastering the complexity along the value chain refer to subchapter 2.6.3.

suitable solutions. Through a financial evaluation of complexity, HCM supports the management of variants and the increase of shared parts across all products. Therefore, it helps to align the external and internal complexity by supporting the whole value chain in offering an optimized product portfolio.

AC always takes into consideration the complexity along the entire product engineering process. Complexity is included as a factor in the topic definition for the development of technologies and components, and in the design of the production process. Furthermore, the marketing and procurement department acts based on complexity targets. As a result, AC has been able to increase the robustness and efficiency of its processes, and to decrease the number of parts, which has increased the transparency within the whole organization.

Caused by a continually expanding number of derivatives as a reaction to higher demands of individualization, AC has confronted an increasing complexity. This complexity is visible in the dynamism of the product portfolio and the production technology, as well as in the diversity of processes. HCM was further triggered by the two drivers *product structure* and *organizational structure*.

Table 26 visualizes the relationship between complexity drivers and HCM at AC. As HCM is conceptualized as a combination of methods for mastering complexity along the value chain, HCM is related to complexity drivers along the entire value chain. A comparison to the methods investigated in the literature and the quantitative study cannot be conducted, due to HCM's interdisciplinary characteristics.

Table 26: Relationship of complexity drivers and methods at AC

	Methods					
	Literature and quantitative study					*AC*
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	HCM
Dynamics of production technology			•	• /+	+	•
Volatility of customer demand	•	•			•	•
Dynamics of product technology	• /+	•	• /+	•		•
Dynamics of product portfolio			•	•		
Dynamics of competition	•					
Variety of customer requirements	•	•	•	•	•	•
Variety of products			•	•		•
Number of customers		•	•			
Uncertainty of delivery (time)		-	-			
Uncertainty of delivery (quality)		-				
Political factors					•	
Legal factors		+		-		
Organizational structure		•				•
Corporate culture						
Number of suppliers				-		
Product structure		-				•
Number of products						•
Variety of production & SC processes						•

• Relationship identified in the literature & cases

+/- Significant correlation identified in the quantitative study

4.6.3.2 The process of identifying and conceptualizing HCM

To identify methods for mastering complexity across all business units, an interdisciplinary team was implemented for three years.[20] The TCT consisted of representatives from marketing, procurement, product development, production, finance, project management, communications, and IT. The representatives operated as a link to the departments, to consult experts along the process of developing the method for mastering complexity holistically ("Holistic Complexity Management" – HCM). The TCT collected data regarding the critical issues of complexity across all business units and the whole value chain.

The procurement stakeholders evaluated the effects of product and component developments on the supplier network. Marketing experts represented the customer perspective and provided information regarding picking rates of variants, as well equipment features. To systematize the percentage of shared components across all business units, the technical development analyzed the product structure. To assure efficient manufacturing processes of product variants on the same production line, the production department analyzed the standardization of parts and manufacturing equipment. The finance department focused on the development of concepts and tools to measure complexity financially. Project managers guaranteed proper time management and a successful coordination of the projects in the departments. To reach all employees with the benefits of the project, communication and training was a crucial pillar of the project. Programmers developed IT tools and processes to increase efficiency and effectiveness within the product engineering process.

In the beginning, some people across all business units did not regard complexity management as necessary to be competitive. The TCT invested time and effort to ensure effective results and to communicate the efficiency benefits. Through seminars and training, the employees learned the procedures and advantages of acting according to HCM. As a result, employees across all business units support the method and implement it actively in their daily processes.

After three years, AC plans to institute organizational changes to integrate the HCM across all business units. The TCT will be broken up and a project management team

[20] The team will be referred to as "Temporary Complexity Management Team (TCT)."

will be formed for each of the product series; two employees in each department across the value chain will monitor the targets of complexity management.

4.6.4 Case IV – Forming Company (FC)

Forming Company (FC) was founded in the 19th century to produce machines for processing sheet metals mechanically. Today, FC has developed into the world's largest manufacturer of stamping presses, offering a wide range of technologies for various industries. The organization is structured into five independent divisions. With more than ten production sites located in Europe, Asia, as well as North and South America, FC delivers individually engineered machines to customers in 40 countries.

As a reaction to increasing complexity, FC has formed a dedicated team to identify and conceptualize methods along the value chain. FC is currently conceptualizing methods regarding standardization of assemblies, establishing preferred series, and searching for reused parts for mastering the complexity in the development and production processes. To increase the efficiency and effectiveness in the order processes, FC is currently evaluating a list of variant configurator tools on the market. In the future, FC will increase the degree of modularization of its products to offer a wide range of products with low internal complexity.

4.6.4.1 Description of methods for mastering complexity at FC

The CMT identified five methods for mastering the complexity along the value chain. Currently, it conceptualizes the methods *standardization of assemblies*, *preferred series*, and *reused parts search*. The benefits and possible solutions for adapting the methods *modularization of products* and *variant configurator* are currently being conceptualized. The characteristics of these methods, as well as their impacts on the entire value chain, will be discussed in the following section.

Standardization of assemblies

The CMT has identified the method *standardization of assemblies* as a solution to increase efficiency in the construction, procurement, and assembly processes.[21] To support construction engineers in creating new products, the CMT identified master

[21] The concept of standardization of production processes is further elaborated on in subchapter 2.6.3.3.

assemblies. The master assemblies help to identify product functions and their related components, thus increasing the percentage of reused parts and components across all product lines. Additionally, clustering of parts in form of standardized assemblies has improved the procurement process. The number of suppliers was decreased by implementing framework contracts. In the future, based on standardized assemblies, the company informant expects a lower number of variants, product changes, and a reduction of different technologies. The standardization approach will therefore hopefully result in a decrease of efforts in planning and organizing of assembly processes.

Through the implementation of standardized assemblies, the informant expects a change in the organizational structure. Currently, decision-making is highly decentralized. The standardization of assemblies encourages the collaboration between FC's various divisions, and the degree of shared assemblies across all divisions will increase. Centralized decision-making is thus regarded as quite beneficial. The informant expects that in future a central department will develop standardized components to use them across all divisions.

Preferred series

Currently, the CMT implements a method to increase the use of parts across the whole product portfolio. The so-called *preferred series* enables the construction, production, and procurement processes of the company to become more efficient. In former times, construction engineers often created from scratch parts, like screws, angles, or sealing rings for every new product. As a reason for the new development, the informant gives non-standardized material for all components and parts, resulting in a high degree of non-transparency. The *preferred series* supports the development process by increasing the transparency over all parts. Based on criteria from all departments, the CMT identified a list of parts to be preferred in future product designs, to reduce their total number and to avoid its increase. Because of the reduced total number of components and parts, the procurer can cluster orders and assign them to selected suppliers. Therefore, FC is able to reduce the total number of suppliers. Furthermore, the preferred series leads to a higher level of standardized production processes. A reduction of process variants through standardized tools and equipment, for example, reduces the workload for employees in assembly processes.

Reuse of parts search

In combination with the method ‘preferred series’, the CMT implements an intelligent search mechanism to increase the share of reused parts. The parts search compares material master data, as well as 3D shapes of parts and components, and indicates their degrees of similarity. Therefore, the effort and troubles in the construction and development processes can be decreased. The informant expects a decrease of new parts as well as an increase of reuse of parts. The clustering of suppliers to increase the efficiency in the procurement processes will also be enhanced.

Variant configurator

In addition, the CMT plans to implement a variant configurator. The benefits of collecting use-cases along the value chain are being investigated. As a first result, the CMT has concluded that the final solution of the variant configurator should support the whole process, from taking the order of the customer to the creation of the Bill of Materials (BOM) for the production. The variant configurator decreases the efforts in the sales, construction, production, and procurement processes for standardized products. Offering final products based on standardized parts and components positively supports the management of customer orders. Hence, the number of individualized products is reduced, which increases the reuse of technologies and parts overall in products. Furthermore, standardized customer orders could facilitate automation of the procurement processes.

Modular product structure

To master the product complexity, the CMT conceptualizes a possible modular product structure. A modular product structure would have several positive impacts along the value chain. In the development stage, product functions could be adapted through the consistent use of modules. Additionally, modularization facilitates the transportation of the final products by structuring the final products in smaller decomposable modules. The informant expects that the modularization will increase the percentage of shared components and decrease the costs along the whole value chain.

Table 27 visualizes the relationship of complexity drivers to the methods *reuse of parts search, variant configurator, preferred series, modular product structure* and *standardization of assemblies* at FC.

The three complexity drivers *variety of customer requirements, variety of products,* and *organizational structure* were considered at FC in order to evaluate implementing a *modular product structure.* The relationship of *variety of customer requirements* and *variety of products* with *MPS* confirms findings in the literature. The complexity driver *organizational structure* was neither identified in the literature nor in the quantitative study as relevant for the implementation of MPS. Some complexity drivers, identified as relevant in the literature and the quantitative study, did not influence BA to implement MPS.

The methods *reuse of parts search, variant configurator, standardization of assemblies*, and *preferred series* were not identified in the literature research as methods for mastering complexity, and as a result were not included in our quantitative study. Therefore, a comparison between quantitative study, literature and FC will not be made.

Table 27: Relationship of complexity drivers and methods at FC

	Methods									
	Literature and quantitative study					*FC*				
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	Standardization of assemblies	Preferred series	Reuse of parts search	Variant configurator	Modular product Structure
Dynamics of production technology			•	• /+	+					
Volatility of customer demand	•	•			•					
Dynamics of product technology	• /+	•	• /+	•						
Dynamics of product portfolio			•	•						
Dynamics of competition	•									
Variety of customer requirements	•	•	•	•	•					•
Variety of products			•	•		•	•	•	•	•
Number of customers		•	•							
Uncertainty of delivery (time)		-	-							
Uncertainty of delivery (quality)		-								
Political factors					•					
Legal factors		+		-						
Organizational structure		•								•
Corporate culture										
Number of suppliers				-			•			
Product structure		-					•			
Number of products						•	•	•	•	
Variety of production & SC processes								•	•	

• Relationship identified in the literature & cases

+/- Significant correlation identified in the quantitative study

4.6.4.2 The process of identifying and conceptualizing methods for mastering complexity at FC

FC embedded a dedicated team[22] to identify and conceptualize methods for mastering complexity within the organization. To identify suitable methods along the value chain, the CMT undertook the following process.

First, the CMT created transparency on the complexity drivers along the value chain. The cost effects of complexity along the value chain created an awareness of its high level. A clear picture of how the complexity and quantity of parts increase the workload within the company confirmed the perceived complexity by the employees in their everyday processes. As a result, the employees were convinced of the positive effects of the methods and supported the implementation process. To reach all the employees with the methods' aim and message, communication had an immense impact on managing the change process.

Second, in collaboration with stakeholders along the value chain, the CMT identified a selection of methods to manage these drivers.

Third, the methods were evaluated and compared with each other. It was important that the methods were suitable for the individual characteristics and challenges of the company; therefore, the efficiency potential was identified throughout the entire value chain.

4.6.5 Case V – Automotive, Inc. (AI)

Automotive, Inc. (AI), founded in the early 20th century, has become one of the biggest automotive companies in the world and offers a broad range of products in different segments. A globally dispersed production network consisting of more than ten manufacturing sites delivers over 1.5 million products yearly to an international customer base.

Increasing individuality of customer demands, along with the dynamics of technologies and competition, have led AI to implement methods for increasing efficiency and effectiveness. The following subchapter describes these methods and their impact on the value chain. The process of identifying and conceptualizing methods for mastering

[22] In the following referred to as Complexity Management Team (CMT).

complexity at AI is also elaborated on. AI implemented standardized production and assembly processes in the past, and it is currently implementing an innovative requirements-engineering process.

4.6.5.1 Description of methods at AI

Standardizing production and assembly processes

The product creation process is organized in the form of Centers of Competence (CoCs). AI created CoCs for various technologies and components of the product to foster the information transfer between departments and optimize the integration of the different perspectives of stakeholders along the product creation process. However, the CoCs were dedicated to individual products, respectively production technologies; the integrated perspective across all products and production technologies thus was missing.

Furthermore, the processes across different product series were not properly aligned, and therefore engineers created individual solutions for each product series. As a result, the number of different parts and components across all products, as well as the variance of the production and assembly processes increased. Switching between different tools resulted in a higher perceived complexity for the shop floor employees.

The overarching standardization approach connects the individual CoCs. Through collaboration between product developers, production planners, and shop-floor employees, AI improved the product and process structures. Standardized parts and components across all product series and a decrease in the number of production processes resulted, among other things, in lighter workloads for the shop floor employees. AI measured the benefits of this method through a reduction of the KPI ‘engineered hours per product’[23]. To coordinate the requirements for standardization across the different stakeholders, AI introduced a department into the organization. This department acted as a moderator, to align the different perspectives for achieving the target of higher standardization within the organization. Projects were derived based on the requirements of the individual stakeholder's targets for development.

[23] Engineered hours per product include only the employee hours needed to mount the product. Therefore it serves as a quantitative measurement for assembly-oriented product design.

Innovating the requirements engineering process

Requirements engineering (RE) is the management process of technical product requirements[24]. First, the marketing department conducts market research to identify the need for new product innovations and specific customer requirements. To fulfill the customer requirements, the product is broken down into four levels – the top level of the product, the system, subsystem, and component level. On the top level of the product, the development department derives the development targets of the product. On the subordinated levels, the development engineers decide on components to achieve the top-level targets. On the component level, engineers derive an extensive list of interrelated development targets for about 1,000 components per product. In case of conflicting targets, a complex process of decision-making starts. AI identified a lack of transparency of the overall requirements, and therefore an optimization potential, regarding the efficiency within the requirements engineering process.

[24] The method requirements engineering is further elaborated on in subchapter 2.6.3.1.

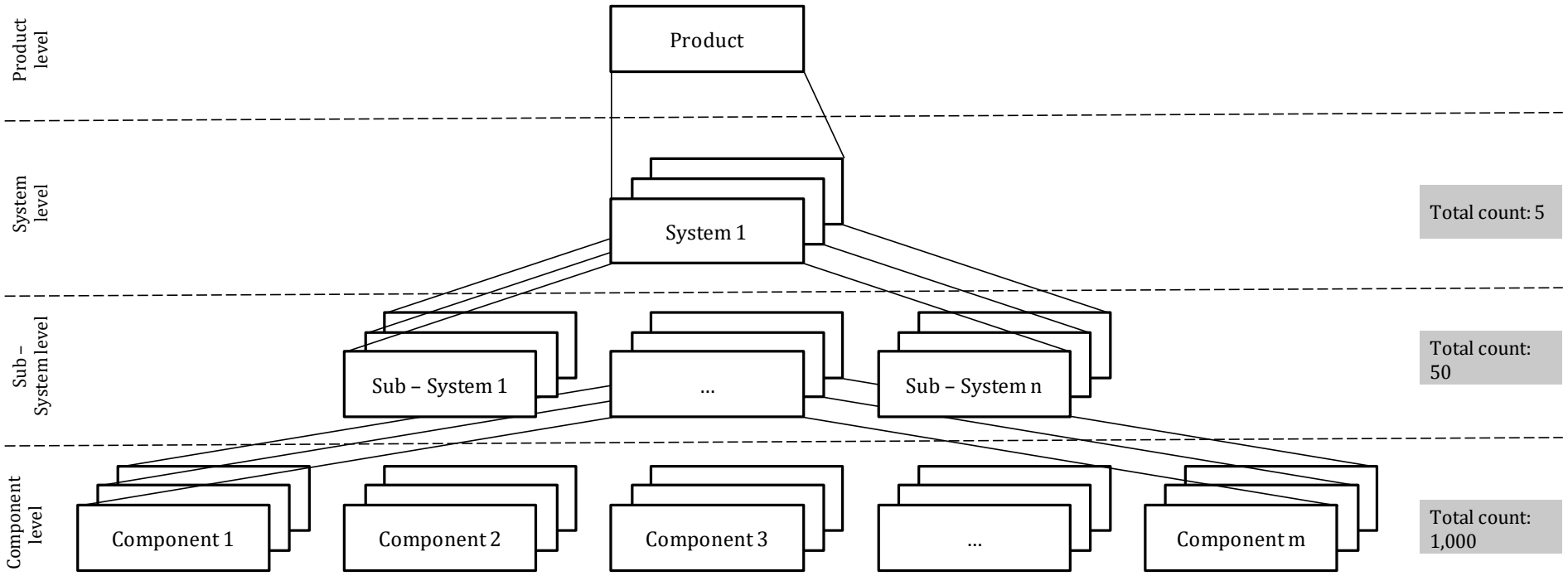


Figure 20: Overview of product levels at AI

Currently, the methods applied to obtain an overview of the requirements are not suitable for the degree of complexity of the interrelationships across all product levels. The methods often focus on individual levels without taking into consideration the effects on the other levels. An overview of all targets and their relationships to the overarching product targets, as well as the customer requirements, is lacking. As a result, it is difficult to identify whether the targets of the components match the customer requirements. To avoid an underfulfillment of customer requirements, development engineers tend to over-engineer components. This may result in a higher price compared to components based on precisely defined requirements.

The non-transparency of the requirements on the different levels of the product (top-level, systems, subsystem, and component level) and their link to the customer requirements created the biggest challenges in the process. It was not clear how the derived targets on the components level contributed to satisfying customer requirements. As a result, the requirements engineering team lacked a solid information basis to discuss conflicting targets. Therefore, a team of stakeholders from all the product levels created a map incorporating all requirements and their relationships across different levels. To manage these interlinked requirements efficiently, AI will implement an IT tool in the future, to ensure that transparency on all product levels will support the customer-oriented development and enhance decision-making.

Additionally, an efficient and effective process of requirements engineering helps to create a detailed description of the development targets of the components, in the form of a product requirements document for external stakeholders. Clear requirements are essential to outsource the development and production of components to suppliers. Furthermore, documenting the requirements on all levels and their relationships initiates a process of knowledge management. The documented relationships between the requirements serve as a basis for the follow-up projects within the whole organization. As a result, the development process becomes more efficient and effective.

Table 28 visualizes the interrelationships of complexity drivers and methods implemented at AI, as well as the relationships identified in the literature and in the quantitative study.

The implementation of RE at AI is related to the seven complexity drivers *dynamics of production technology, product technology, dynamics of competition, variety of customer requirements, variety of products, variety of production and supply chain*

processes, and *number of products.* The relationship of *variety of customer requirements* and *dynamics of product technology* with *RE* was also present in the literature. Some complexity drivers, identified as relevant in the literature and the quantitative study, did not influence AI to implement RE.

Volatility of customer demand, organizational structure and *number of customers* was identified in the literature as being related to *RE*. In the quantitative study a significant negative correlation was identified between uncertainty of delivery (quality and time) and RE, therefore a strong influence of *uncertainty of delivery* results in a low implementation degree of the method *RE*. This relationship could not be identified at AI, and is counterintuitive anyway: RE would support reducing the complexity driver *uncertainty of delivery.*

Furthermore, a significant positive correlation between *legal factors* and *RE* was identified in the quantitative study. Thereafter, a strong influence of the complexity driver *legal factors* results in a greater implementation degree of RE. Additionally, a significant negative correlation between the complexity driver *product structure* and *RE* was identified in the quantitative study. These complexity drivers did not influence AI to implement RE.

The method *standardization of production and assembly processes* was not identified in the literature research as being effective for mastering complexity, and as a result was not included in our quantitative study. Therefore, a comparison between quantitative study, literature and AI regarding this method will not be drawn.

Table 28: Relationship of complexity drivers and methods at AI

	Methods						
	Literature and quantitative study					*AI*	
Complexity drivers	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	Standardization of production and assembly processes	Requirements engineering
Dynamics of production technology			•	• /+	+		•
Volatility of customer demand	•	•			•		
Dynamics of product technology	• /+	•	• /+	•			•
Dynamics of product portfolio			•	•			
Dynamics of competition	•						•
Variety of customer requirements	•	•	•	•	•		•
Variety of products			•	•		•	•
Number of customers		•	•				
Uncertainty of delivery (time)		-	-				
Uncertainty of delivery (quality)		-					
Political factors					•		
Legal factors		+		-			
Organizational structure		•					
Corporate culture							
Number of suppliers				-			
Product structure		-					
Number of products						•	•
Variety of production & SC processes						•	•

• Relationship identified in the literature & cases

+/- Significant correlation identified in the quantitative study

4.6.5.2 The process of identifying and conceptualizing methods for mastering complexity at AI

At AI, an embedded, dedicated team identifies and conceptualizes methods[25] for increasing efficiency and effectiveness of processes along the value chain. The 'methods team' regularly conducts surveys with stakeholders to identify their demands and improvement suggestions. Their data collection process via questionnaire involved stakeholders along the value chain, for example, development engineers, production planners, and shop floor employees.

The results of a previous survey indicated improvement potential in the product and production structures. Stakeholders from the production department (production planner and shop-floor employees) indicated a large variety in the production and assembly processes. Because of the large variety of parts across the product variants, the shop-floor employees needed to switch between different tools and manufacturing equipment. A team consisting of product designers, production planners, and shop-floor employees identified standardized parts across products. As a result, the number of parts, along with the variance in production and assembly processes, decreased.

In a recent survey conducted by the 'methods team', the development engineers rated the complexity within the requirement engineering processes as too high. The large number and great variety of customer requirements, new technologies in products and production, regulations, as well as dynamics of competition require efficient and effective management of requirements. As a result, innovating the "requirements engineering" was one of the most highly prioritized topics in the development department.

4.7 Cross-case analysis

Eisenhardt (1989, p. 540) states that "the key to good cross-case comparison is counteracting these tendencies[26] by looking at the data in many divergent ways". As a result, cross-case analysis helps the researcher to "go beyond initial impressions" (Eisenhardt, 1989, p. 540). The following subchapter outlines the cross-case analysis of the five study cases, aiming to find similarities and differences between the companies

[25] In the following referred to as 'methods team.'

[26] She refers to the first conclusions of researchers based on the insights from initial analyses of information.

in identifying and conceptualizing methods for mastering complexity. Table 29 depicts the characteristics of the case companies, including the kinds of products produced, types of manufacturing, types of order processing, number of years working in complexity management, the linkage of complexity management in the strategy of the organization, as well as the degree of centrality in decision-making.

Table 29: Overview of characteristics of case companies

	BA	***PC***	***AC***	***FC***	***AI***
Kind of products produced	Assembly groups (ca. 100 parts)	Process industry goods	Machines (ca. 1,000 parts)	Heavy machines	Machines
Type of maufacturing	Mass production (> 1,000 pieces/month)	Mass production	Mass production	Piece production (<20 pieces/month)	Mass production
Type of order processing					
ETO				•	
MTO	•		•		•
CTO					
MTS	•	•			
Experience in complexity management [years]	15	10	20	1.5	15
Complexity as part of your strategy	Complexity integral part of strategy	Complexity considered during strategy formulation process	Complexity considered during strategy formulation process	Complexity considered during strategy formulation process	Complexity integral part of strategy
Decision making (decentral - central)					
Marketing	decentral	central	decentral	decentral/ central	decentral
Sales	decentral	decentral	decentral	decentral	decentral
Pricing	central	decentral/ central	decentral/ central	central	decentral/ central
Product management	decentral	central	decentral	decentral	decentral
Product design	central	decentral/ central	central	decentral	central
Modular product platform design	central	n.a.	decentral/ central	decentral/ central	central
Product technology choice	central	central	decentral	decentral/ central	decentral/ central
Procurement	central	central	decentral	central	decentral
Make-or-buy decisions	central	central	decentral	central	decentral
Selection of the production technology	central	central	decentral	central	decentral
Production capacities	central	central	decentral	decentral/ central	decentral
Quality level	central	central	decentral/ central	central	central
Process management	decentral/ central	decentral/ central	central	decentral/ central	central

The following subchapter describes the common influencing factors which identify and conceptualize methods for mastering complexity in the manufacturing industry.

4.7.1 Value chain stages

The within-analysis of the individual cases describes the influence of the methods on the value chain stages (subchapter 4.6). Table 30 shows an overview of all methods and their influences on the value chain. It shows that the methods cover the entire value chain, including supporting processes, for example, quality. The results can be generalized and applied to every method along the value chain of manufacturing companies.

Table 30: Overview of the influence of methods on the value chain

Case Company	Method	Value chain					
		Marketing/ Sales	*Product development/ Construction*	*Production/ Assembly*	*Supply chain*	*Procurement*	*Supporting processes*
BA	*TSM*		•				
	MPS	•	•	•	•	•	
PC	*PO-SOP*	•	•	•	•	•	Quality, Organizational structure
AC	*HCM*	•	•	•	•	•	
FC	*Standardization of assemblies*		•	•		•	Organizational structure
	Preferred series	•		•		•	
	Reuse of parts search		•				
	Variant configurator	•	•	•		•	
	Modularity of products		•	•	•		
AI	*Standardization of production*		•	•			
	RE		•	•		•	Knowledge management

4.7.2 Influencing factors for identifying and conceptualizing methods

The cross-analysis of the five case companies reveals six common influencing factors for identifying and conceptualizing methods for mastering complexity in the manufacturing industry.

First, the influencing factor ‘stakeholders’ describes people and functions involved in the project. Many case companies mentioned the importance of both strategically well-positioned executives and experts, product- or production-related. For example, PC, AC, FC, AI, and BA, in the case of MPS, involved both the strategic and the expert group of stakeholders. BA mainly focused on experts during the project, with respect to the method of TSM.

Second, all case companies took into consideration the ‘complexity drivers’ of their organization. The complexity drivers describe the factors influencing the degree of complexity a company is facing. Within the individual cases, the role and the type of these drivers differ. On the one hand, some companies solely perceived an increase of complexity, without actually measuring it (BA). On the other hand, some companies measured isolated key performance indexes (KPI’s in the case of AI and AC) or even evaluated the impact within the processes (PC, FC).

Third, in the manufacturing industry the ‘technical characteristics’ of the products and processes deliver valuable information to evaluate the suitability of methods for mastering complexity. This information is related to analyzing the product structure, materials, and technology or production process flows and parameters.

Fourth, a crucial element in the individual cases is the ‘interdependency of methods’ for mastering complexity. This present study identified three types of interdependencies between methods:

- Different methods are precondition for the method in question and therefore should be implemented first. For example, BA’s MPS served as a precondition for the subsequently derived method TSM.
- Methods can support each other and should be implemented in parallel. For example, AI identified a close relationship between modularizing of products and standardizing production processes.

- A method may foster the implementation of other methods as a different perspective on processes and structures is achieved. For example, at PC the digitalization approach of the entire SOP landscape was fostered through the PO-SOP, as standards of documents and processes were identified.

Fifth, ‘strategy’ sets guidelines and supports consistent decision-making. Some case companies based their methods for mastering complexity clearly on the strategy of the company. Other case companies regarded the strategy of the company as one input source out of many.

Sixth, since complexity affects many aspects and processes of an organization, ‘interdisciplinary project teams’ help to involve many perspectives on this topic and to evaluate the influence of methods holistically. Furthermore, the ‘organizational anchoring’ of the project teams during the project, as well as after implementing the method, is crucial for its success.

Table 31 shows the individual manifestations of the elements in the case companies during the process of identifying and conceptualizing the methods for mastering complexity. It demonstrates that all case companies included every element in their projects for identifying and conceptualizing these methods. The following subchapter describes the individual manifestations of the elements in the cases.

Table 31: Influencing factors at the case companies

Case Company	Method	Influencing factors					
		Stakeholders	*Technical char.*	*Strategy*	*Interdependency of methods*	*Complexity drivers*	*Interdisciplinary project teams*
BA	*TSM*	•	•	•	•	•	•
	MPS	•	•	•	•	•	•
PC	*PO-SOP*	•	•	•	•	•	•
AC	*HCM*	•	•	•	•	•	•
FC	*Standardization of assemblies*	•	•	•	•	•	•
	Preferred series	•	•	•	•	•	•
	Reuse of parts search	•	•	•	•	•	•
	Configurator	•	•	•	•	•	•
	Modularity of products	•	•	•	•	•	•
AI	*Standardization of production*	•	•	•	•	•	•
	RE	•	•	•	•	•	•

4.7.2.1 Stakeholders

The individual approaches of the five case companies regarding the inclusion of stakeholders will now be outlined. For identifying and conceptualizing methods for mastering complexity, various stakeholders need to be involved. Table 32 shows an overview with respect to the stakeholders of the case companies in this present study. All case companies involved different stakeholders along the value chain, experts, and top managers. The cross-case analysis shows that the case-companies involved them in a variety of ways: There was isolated involvement through interviews, constant involvement through being part of the project team, and inclusion of members representing a different perspective, consulting and project management teams.[27]

In isolated interviews, the requirements of the stakeholders are identified, or pre-development solutions are tested. The project teams with stakeholders benefit from continuous challenging and active participation of the stakeholders in identifying and conceptualizing the solutions. Interdisciplinary project teams incorporate different characteristics, which will be elaborated in subchapter 4.7.2.6. The present author was a member of the research team in the projects conducted with BA and PC in identifying the need for methods for mastering complexity and conceptualizing these methods. The research team added an external insight on the topic of complexity in these companies. A similar approach was conducted at FC, AC, and AI. Project management teams supported identifying and conceptualizing complexity-mastering methods.

[27] The influencing factor of interdisciplinary project teams is described in subchapter 4.7.2.6.

Table 32: Stakeholders at the case companies

Case Company	Method	Stakeholders							
		Marketing and sales	*Production planner*	*Product developer / Constructor*	*Logistics manager*	*Shop-floor employee*	*Top-management*	*Project management team*	*Other stakeholders*
BA	*TSM*			•			•		Lean developer; external stakeholders
	MPS		•	•					
PC	*PO-SOP*		•	•	•	•	•		Quality (PKM mnanagers)
AC	*HCM*	•	•	•				•	Finance, IT, procurement
FC	*Standardization of assemblies*						•	•	
	Preferred series			•			•	•	Procurement
	Reuse of parts search			•			•	•	Procurement
	Variant configurator	•	•	•			•	•	
	Modularity of products	•	•	•			•	•	Procurement
AI	*Standardization of production*		•	•		•		•	
	RE	•	•	•				•	

BA's MPT was established to identify and conceptualize the MPS. The MPT consisted mainly of development engineers from the mechanics, electronics and software teams. The process of analyzing the product portfolio and components, along with conceptualizing the MPS, involved stakeholders from the development and production department. To gain access to further insights within BA, the MPT interviewed various stakeholders along the value chain.

The research project at BA aimed to identify the need for a TSM and to conceptualize this method. To do this, stakeholders from various departments were involved in the project. From the top management level, the head of development of the actuator division was individually involved in workshops to evaluate the development status of the project. As part of the actuator division, both the head of development from the department "electronics" and "motor" played an essential role in identifying the needs of the user. To align this project with ongoing optimization activities, an interdisciplinary lean developer took part in the project as well. The primary contact was an engineer in the "motor" department. He was the initiator of the project, coordinated all meetings, and delivered the necessary information to conceptualize the TSM.

Working in interdisciplinary workshops, the research team identified four main user profiles of the TSM: The developer, the executives from each department, the project leader, and the division leader. The research team conducted interviews with experts of these four user profiles to create use-cases for the TSM. The tasks and responsibilities of the developers entailed searches for existing components and solutions, as well as the maintenance of the database. While being responsible for the strategic development of the TSM, the executives from the departments were also required to add further elements. To gain an overview of the efforts and costs of development projects, the project and division leaders mainly used the TSM as a search tool in the early stages. Furthermore, they reported missing components or solutions, as well as inconsistencies.

The CMT at FC identified the need for methods for mastering complexity through interviews with stakeholders along the value chain. The CMT was a small team which did not encompass all stakeholders along the value chain. Through isolated inclusion of the strategically well-positioned executives and technical experts, the CMT identified methods and analyzed their applicability, along with their suitability for the organization. The informant regarded the support from top management as crucial to enable the implementation of complexity-mastering methods within the organization. To standardize assemblies, the CMT identified the needs of the construction, production

planning, and procurement department. The conceptualization of both the *reuse of parts search* and the *preferred series* involved employees from the construction department and from the entire purchasing process. The process of deriving criteria to select a configurator involved stakeholders along the whole value chain – primarily sales and construction. Conceptualizing modular product structures involved development engineers as well as sales, production, and procurement experts.

PC and AC actively involved stakeholders along the value chain as well as top management executives throughout the entire project.

The insights from a research project at PC in analyzing the current SOP architecture and the resulting costs will be discussed in this dissertation. This research project also conceptualized an innovative SOP architecture. To identify and conceptualize the method, the research team included various stakeholders. From the top management level, the head of corporate quality was involved in the project, to align the project with PC's strategic orientation. Executives from the PKM, as part of the corporate quality department, played an important role in identifying weaknesses and the efforts in the corporate SOP processes. To identify the needs along the SOP creation process on site level, stakeholders – supply chain managers, production planners, shop-floor workers, executives, and site heads from five sites in Germany – provided insights from their perspectives. The research team collaborated with the head of PKM and an interdisciplinary executive belonging to the corporate quality division. As a result of all this, the structure of the model and ideas for the future SOP architecture were derived.

AC regards complexity as relevant for all departments along the product engineering process. Furthermore, top management executives initiated and led the project. As a result, the conceptualized method supported decision-making based on a holistic approach of complexity effects along the entire value chain and within all supporting departments. Therefore, the TCT involved stakeholders from all departments along the product engineering process, including marketing & sales, procurement, technical development, and production. As supporting departments, the TCT also included finances and IT. The TCT members stated the requirements of their departments and served as a connection to experts for gathering further information. While conceptualizing the HCM, the TCT initiated method projects in the individual departments. The TCT also included a sub-team of project managers to support the stakeholders in their department method projects. Furthermore, top management executives initiated and led the project. As a result, the conceptualized method supported

decision-making based on a holistic perspective of complexity effects along the entire value chain and in all supporting departments.

AI conducted a combination of separate interviews with dedicated project teams throughout the whole project period. The ‘methods team’ regularly interviewed various stakeholders along the value chain to identify challenges and improvement suggestions. If an improvement potential was identified, the ‘methods team’ initiated a project and set up a suitable team. To standardize the production, development engineers, production planners, and shop-floor employees worked together on the project. The development engineers identified the criteria for standardizing components and parts, to ensure the compatibility with selected products of the product portfolio. To guarantee manufacturability, production planners and shop-floor employees contributed to the requirements of the various assembly processes regarding tools and manufacturing equipment. The alignment of the various stakeholders’ requirements led to higher efficiency and effectiveness in the development, as well as production and assembly processes. Measuring and communicating the process improvements helped to create an awareness of complexity among all stakeholders.

In a recent survey conducted by the ‘methods team’ innovating the requirements engineering process was one of the top priorities mentioned by the developers. To conceptualize the requirements engineering processes, AI involved developers from all product levels in the analysis of the current processes. Discussions between developers about conflicting targets of components were inefficient and ineffective due to non-transparency of the components’ contribution to the exaggerated customer requirements. Therefore, the developers of the products contributed towards establishing the relationships of sub-level to top-level, and the customer requirements.

Some case companies included a non-specialist[28] perspective in their projects. FC and AI established a project management team to identify needs and to support conceptualizing methods. The non-specialist perspective helped to question the current system and to understand it better. Furthermore, the project management team gained methodological knowledge about mastering complexity and leading change projects.

[28] Non-specialist refers to a person without knowledge of the company’s processes and products.

This present study relies much on the insights from research projects with BA and PC, which established an external perspective on the topic of complexity management and identified requirements of the stakeholders along the value chain.

Additionally, the cross-case analysis shows that the case companies applied different approaches to initiate complexity-mastering methods. PC and AC applied a top-down management approach. The top-management of AC created a vision and initiated a company-wide program for mastering complexity – the HCM (Holistic Complexity Management). The HCM entailed targets for the entire company, which were broken down into sub-targets for the individual departments. PC also identified the idea of an improved and process-oriented SOP architecture within the top management. They involved individual stakeholders along the value chain and in the management of the SOPs to develop the method.

AI, BA, and FC conducted a bottom-up approach. At AI, a project management team consulted the individual departments in their daily processes and identified improvement potential with them. For example, the standardization of the production was initiated by a shop-floor employee. A similar approach was applied at FC; the CMT was initiated by the top management. At BA, both methods (TSM and MPS) were initiated by developers or project managers. The bottom-up approach actively involved employees during the process of identifying a possible solution and was therefore beneficial in limiting the resistance of employees against new methods.

4.7.2.2 Complexity drivers

All case companies regarded complexity drivers as input for identifying complexity-mastering methods within their organizations. The cross-case analysis revealed that the role of complexity drivers differs in each individual case. AC and AI analyzed complexity drivers and their increase within recent years. For example, AC calculated a tripling of its product portfolio in the last two decades. However, in contrast to PC and FC, AC and AI did not evaluate the impact of the complexity drivers on the processes along the value chain. The project teams at PC and FC conducted a detailed assessment of the complexity drivers and evaluated the impact on the various processes within the SOP management process, respectively along the value chain. Based on this assessment, the project team identified an initial list of methods for mastering complexity. At BA, the project team for the MPS and the TSM perceived great strains in their processes as a result of complexity drivers. However, in contrast to AC and AI, the complexity

drivers were not evaluated. Table 33 visualizes the relevant complexity drivers and related methods at the case companies.

Table 33: Relationship of methods and complexity drivers at the case companies

Case Company	Method	Complexity Drivers: *Variety of products*	*Variety of customer requirements*	*Legal factors*	*Number of products*	*Dynamics of product technologies*	*Dynamics of production technologies*	*Variety of production & supply chain processes*	*Others*
BA	*TSM*	•	•	•	•				
	MPS	•	•		•			•	
PC	*PO-SOP*	•	•	•	•	•	•		
AC	*HCM*	•	•		•	•	•	•	Organizational structure
FC	*Standardization of assemblies*	•			•				
	Preferred series	•			•			•	Number of suppliers, product structure
	Reuse of parts search	•			•			•	
	Variant configurator	•			•			•	
	Modularity of products	•	•						Organizational structure
AI	*Standardization of production*	•			•			•	
	RE	•	•	•		•	•		Product structure, Dynamics of competition

Now the individual approaches of the case companies regarding the involvement of complexity drivers in their projects will be outlined.

At AC, the TCT initiated HCM to reduce the impact of diverse complexity drivers. Based on the individualization trend, the number and variety of customer requirements increased. As a result, AC developed more derivatives, which led to a broader product portfolio, including a higher number of product variants. The internal structures, along with production and supply chain processes, became more complex. Furthermore, the competitive pressure regarding the innovation of technologies and digitalization within the processes steadily increased. To manage these effects of complexity on the organization, AC decided to develop the HCM.

Increased complexity within the production processes at AI was identified through the KPI 'engineered hours per product'. It indicated the need for improvement. High process variance as a result of the broad product portfolio, induced by individualized market demand, led to an increase of the 'engineered hours per product.' Offering a product series in 130 countries with four product versions and various options required the use of standardized parts across all products. Furthermore, standardizing the tools and manufacturing equipment in the assembly processes decreased the process variance and led to more robust processes.

Innovating the requirements engineering processes originated from the diverse complexity drivers' AI faces. Since the market segments had become more individualized, the resulting variety and volatility of the customer requirements created non-transparency and complexity within the requirements engineering processes. Another driver was the product structure. It consisted of four levels[29] – from the top product level to the component level. Since, the levels were interrelated with one another, linking the increasing number of customer requirements to the individual elements of these layers became more challenging. Dynamic changes in product and production technologies resulted in increased development efforts. The number of laws and regulations, together with its dynamic changes, created non-transparency, and required the system to become more adaptable. Furthermore, the competitive dynamics on the market required fast, efficient, and effective processes to enable innovations.

[29] For more details of the product structure compare the case description of AI in subchapter 4.6.5.

PC's organization consists of three business fields, each offering a wide-ranging product portfolio, including various product variants. Delivering these products is accomplished through a widespread global production network consisting of complex production and supply chain processes. Since all products and processes are highly regulated, every change is accompanied by a change of at least one SOP. To maintain a competitive advantage in the pharmaceutical industry, PC continuously innovates its product technologies. In a research project with ITEM-PM, the process of managing the SOPs was analyzed. As a result, the research team identified various complexity drivers which affect the creation process of SOPs. The *number of products*, *variety of products, dynamics of product* and *production technologies* increased the number of SOPs in the system. Therefore, identifying the impact of regulatory changes on PC's SOPs became a challenge. Furthermore, the number of people from different functions involved increased the coordination efforts in the writing and reviewing process. To efficiently and effectively create and maintain a consistent SOP System, PC aimed at mastering these complexity drivers. Furthermore, based on the complexity drivers, the research team optimized the conceptualization of the process-oriented SOP architecture.

At first, the FC's CMT analyzed the complexity drivers in its value chain processes, and their impacts on costs. Based on the individual manifestations of the complexity drivers, FC identified a list of methods for mastering them. The informant of FC indicated a significant contribution of the driver *number of components and parts* to the company's complexity. The product structure and the necessity for individual design of product parts, increased the share of customer-specific products: For example, tools were usually designed explicitly, i.e. custom made for the customer. The informant estimated that approximately 5-10% of machine was customer-specific. Therefore, standardizing and reusing the entire product for more than one customer was not feasible. FC offers many different product functions to the customer, which has led to an enlarged product portfolio. Furthermore, much duplication exists within the system, because the different divisions use synonyms for the same parts or components. This also led to an increasing number of suppliers in the past. The broad product portfolio has been created in various divisions, with individual products and small product quantities.

To master these various complexity drivers, the CMT aspires to apply a combination of methods. The alignment of both, the variant configurator and the reuse of parts search, helps in managing the variety in the sales, order, and production processes. Increasing the level of standardization across all divisions helps to reduce the number of

components. The method of modularization of the products helps to decrease the complexity induced through the product structure, as well as the variety of customer requirements.

BA perceived greater efforts along the value chain created by an increase of diverse complexity drivers. The individualized customer requirements led to a perceived increase in product variants. Different sizes, materials, and colors of components for each of the different product lines resulted in an inefficient variety. Additionally, the variety of the product portfolio affected the production processes. Different tools for components with similar functions resulted in high investments and impeded the implementation of innovative technologies. Hence, BA aimed to reduce the number of components and assemblies by introducing modular product structures.

The perceived increase of the complexity drivers within the development department provided the primary motivation for BA to implement the TSM. The large number of components and parts resulted in a lack of transparency regarding their combinability. To obtain an overview of the relationships between the components, BA collected knowledge within the company through expert interviews.

In some cases, it appeared that searching for suitable existing solutions required more effort than the development of new components. As a result, the informant perceived a decrease in the percentage of shared components of overall product variants. This led to a lower degree of reusability of components, indicating a low degree of maturity. Components at a low level of maturity made it harder for BA to create a high quality of the final products. To assure a high quality of the final products, components with an advanced maturity stage are preferred. This undesirable situation was one motivation for the TSM. The TSM provides an overview of suitable existing components based on the characteristics and requirements of the final product. By increasing the transparency within the company, including all components and the product portfolio, the TSM supports the developer in configuring customer-individualized products.

4.7.2.3 Technical characteristics

The technical characteristics of the case companies played a pivotal role in identifying the feasibility of the decision-making process to select methods for mastering complexity. Based on the cross-case analysis, the research team identified a difference in the methods selected, depending on the “type of order processing” and the “kind of products produced”.

Methods for increasing flexibility in processes and product design have been implemented at BA, AC, AI, FC. All of these companies apply this type of order processing, depending on a customer order. FC applies ETO, FC, whereas BA[30], and AI apply ATO/MTO. For example, the TSM improves the speed in the order processes at BA.

PC applies MTS as its type of order processing. MTS as order processing is characterized by processes only dependent on internal planning, with a long planning horizon. Therefore, increasing the flexibility within the processes is not necessary to be competitive. The method applied, an innovative SOP architecture, does not increase the speed in the order processes but in the development of new products. Furthermore, it increases the stability of all processes and serves as a basis to standardize processes, and it promotes an increase in quality.

BA, AC, FC, and AI offer discretely manufactured products. The applied methods of these companies show the impact of highly individualized products on the production and business processes. The management of the interdependency between the modules and components of the products provides the focus of the methods applied at BA, AI, AC, and FC. PC produces pharmaceutical products, and the choice of method shows the highly regulatory impact on the business and production processes.

Individual case-companies and how they include technical characteristics in their projects to identify and conceptualize methods for mastering complexity will now be discussed.

To identify the potential benefit of its methods, BA analyzed the technical characteristics of products and processes. Before implementing the MPS, BA's product variety consisted mainly of different variants of components with similar functions. The development engineers analyzed the functions and characteristics of components across all product lines and decided to cluster them. Thus, the technical product characteristics allowed for a modularization of the product structure. Furthermore, the production processes permitted implementing methods to standardize and automate.

The primary function of an actuator, the movement of a flap (e.g., for ventilation), can be broken down into three sub-functions. Individual components of the product support these sub-functions. The components motor, motor controller, and power adapter

[30] BA applies ATO as order processing to finish customer orders. To produce the components MTS is applied.

together facilitate the sub-function ‘create torque’. The gearbox is responsible for the ‘transmitting of the torque’. The individual components are closely related to one another, and so the characteristics of each component need to be aligned with the others. In every customer project, the components’ interrelationships are relevant in choosing the right configuration to ensure functionality.

The technical characteristics of the interrelationships of the products helped to conceptualize the TSM. In the process of identifying the interrelationships of the components, the degree of complexity in the configuration process of an actuator became apparent. By conducting interviews and screening company documents the relationships between the components, consisting of complicated formulas and various interlinked conditions, were established iteratively. Therefore, the project team expected that the TSM would closely support the developer in mastering the complexity in the configuration process of actuators.

The technical characteristics of the product and the production processes of AC affect the feasibility of methods along the entire product engineering process. Thus, the project of identifying and conceptualizing required a holistic approach (HCM). By involving stakeholders from all departments along the product engineering process, the TCT integrated multiple requirements into identifying and conceptualizing the HCM. Since the development of products is strongly interrelated with internal production and supplier processes, to develop IT tools to support the stakeholders along the value chain in managing complexity, the programmers involved the structure of products as well as production and supply chain processes.

FC’s products consist of more than 10,000 parts; the technical characteristics of products and processes define the feasibility of methods for mastering complexity. The product structure allows modularity to increase the percentage of shared components across all divisions. Based on technical drawings and characteristics, the CMT identified the reuse of parts search as beneficial for creating transparency. To standardize components and assemblies, its technical functions were analyzed and clustered.

AI’s technical characteristics of products and processes facilitated the implementation of both methods *standardizing production and assembly processes* and *innovating the requirements engineering process*. The technical characteristics of the products and the production processes supported the standardization target. AI’s modularization approach of products facilitated the standardization of production and assembly processes. A team of developers revised the individual requirements of the products to

identify standardized parts across selected products. Based on the production characteristics, production planners, and assembly workers identified standardized tools and manufacturing equipment for selected products.

To innovate the RE processes, AI's 'methods team' considered the technical characteristics of the product and production. The product structure, consisting of four levels[31] – with five systems, 50 subsystems, and 1,000 components – supported the implementation of the method. AI was able to visualize the relationship between the targets on all levels and its contribution to fulfilling exaggerated customer requirements. Since the manufacturability of products is an essential factor in increasing efficiency and effectivity, the production and product requirements have to be aligned. Managing these partly conflicting requirements, as well as their diverse interrelationships, is a complex task, requiring support through an innovative process.

The primary function of the SOPs is the documentation of processes to ensure compliance to regulations. SOPs incorporate descriptions of working instructions for stakeholders on various levels. To create the content, authors and reviewers from different departments are involved in a complicated process entailing the evaluation of regulatory changes, writing and reviewing activities, as well as the training of the future SOP. To facilitate this interdisciplinary cooperation, an IT-system supports the entire process. To identify the benefits of innovating the SOP architecture, these characteristics play an important role, and their insights also help to derive conclusions for the elaboration of the final architecture.

4.7.2.4 Strategy

All case companies link complexity management and their strategy. Based on the data of the benchmarking project,[32] the research team identifies the involvement of complexity in the strategy formulation process of the case companies. BA clearly stated that complexity is an integral part of its strategy. PC, AC, and FC take complexity into consideration in the development of the organization's strategy. This shows the relevance of the strategy in the process of identifying and conceptualizing methods for mastering complexity. All the case companies integrated strategy into their projects.

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[31] For more details of the product structure compare the case description of AI in subchapter 5.6.5.

[32] The benchmarking project "Global Complexity Management" is described in Chapter 4.

The following subchapter includes descriptions of the individual company cases, focusing on the involvement of strategy in the process of identifying and conceptualizing the method for mastering complexity.

The statement "Rapid and customized execution is the key"[33] accentuates the importance of speed and individuality in the delivery process of BA. BA ensures delivery of products within 1-2 days from the time of order placement by the customer. Furthermore, a strong focus on its strengths is part of BA's strategy. The development of components and the final dimensioning of engines is performed internally, whereas manufacturing of components is outsourced to suppliers. To support this strategy, BA implements, among other things, the methods modularity of products and the TSM.

The modular product structure consists of standardized interfaces between modules. As a result, individual modules can be developed independently from each other. This allows BA to further focus on its core competencies: The development of components, and the final dimensioning. Suppliers deliver individual modules and can focus on the optimization of its assembly and production processes.

The TSM supports the development department in fulfilling this criterion more efficiently. As described above, primarily through the reduction of iterations at the end of a project the TSM helps to increase the speed in the development projects. Furthermore, the TSM helps to find white spots in the product and technology portfolio of the company, helping to customize and optimize the product portfolio. Also, the management attention to the project showed alignment with the strategic orientation of BA. As a conclusion, the strategic orientation served as a guideline in the conceptualization process of the TSM.

PC's mission is to provide products to improve the lives of human beings. In accordance with this purpose, the company focuses on research, development, and production of high-quality medicines. Future investments will contribute to a more diversified product portfolio. PC sustains these targets through its core competencies. Among them, quality management helps to achieve the highest product standards and to fulfill requirements from regulatory authorities. SOPs support the employees in operating in a standardized way, to comply with regulatory requirements and to create quality products. Innovating

[33] Taken from the official document "Mission and Vision" of BA.

the architecture of SOPs facilitates adaptation and assessment, therefore affecting the processes for delivering these products and ensuring compliance.

AC aligns its strategy with three megatrends of future mobility – digitalization, sustainability, and urbanization. Customers lead a digital lifestyle and interconnect many parts of their daily lives. Therefore, AC wishes to create interconnected products to deliver unique digital experiences to its customers. Through the development of innovative, sustainable powertrain technologies, AC supports customers in reducing their environmental emissions, researching innovative mobility concepts, like autonomous driving and flight taxis to improve life in urban areas.

AC aligns HCM with its strategies, aiming to digitalize all processes and to increase the percentage of shared components, such as electric architectures, across all products. AC tailors its product portfolio and its development activities to the customer needs and preferences. Therefore, AC can phase out unwanted product configurations and free up resources to develop innovations. As a result, HCM also contributes to achieving the strategic pillars of sustainability, urbanity, and digitalization.

FC has coordinated the methods for mastering complexity with its strategy of incorporating the various divisions into one legal entity. Especially the standardization of assemblies and preferred series helps to create a structure to achieve this goal. FC's business consists of offering a small volume of partly individualized products. To be competitive, the CMT plans to modularize products and standardize assemblies. The *reuse of parts search* supports effective implementation. Therefore, the CMT supports FC's strategic orientation through the list of planned methods.

AI's strategic orientation supports both methods, *standardizing assembly processes* and *innovating requirements engineering*. As part of the former strategy, AI strives to implement a variant management program to achieve growth and profitability targets. The influence of market complexity requires innovative product and process structures. Therefore, linked with modularizing the product structure AI has also increased the standardization of the assembly processes.

The main components of AI's current strategy promote innovating the process of *requirements engineering*, since customer orientation is one of the most important aspects of AI's strategy. Requirements engineering aims at increasing the focus of development activities on customer needs. Clear visibility on how the development targets on all product levels contribute to the customer requirements helps to support their fulfillment. Additionally, higher profitability is a central element of AI's strategy

for achieving the goals inherent in the "development of future technologies." Innovating the requirements engineering helps to increase the efficiency within the development processes and therefore to unleash resources to innovate.

4.7.2.5 Interdependency of methods

The interdependency of methods is an essential factor when implementing new methods. Four out of the five case-companies took into consideration the relationship of the implemented method to other methods within the organization. As an example, BA adapted its supply chain after the implementation of the product structure. As a result of the modular product structure, the research team was able to conceptualize the *TSM*, in cooperation with development engineers at BA. AC stated that their *HCM* is not interrelated with other methods within the organization. However, AC integrated the entire value chain into its *HCM*. The individual methods of the departments along the product engineering process are closely related to one another.

The centralized degree of decision-making within the organization seems to determine whether the decision makers take into consideration the interrelatedness of methods — the more centralized the decision-making, the better the overview of the whole organization. Hence, the visibility of dependencies between methods should be greater if the decision-making is centralized. Therefore, while planning a method for mastering complexity, the decision makers can identify methods to be implemented before, parallel to it, or after.

Central decision-making helps those responsible to keep track of the overall picture of the company; however, it lacks the expert perspective in the individual departments along the value chain. In some case companies, the expert perspective on products and processes was crucial in their projects. Exclusively considering top-management insights could, therefore, lead to false decision-making. As an example, AI integrated top management and technical experts into their projects, and as a result it planned the modular product and production structures parallel to each other.

BA implemented the modular product structure without planning modular production structures parallel to it. After BA identified the success of this move and realized a decrease of process variation in the production, the modular production structures were conceptualized. AI, on the other hand, analyzed synergies beforehand and therefore planned the modular product and production structures parallel to each other.

Another factor which influences the visibility of interrelatedness of methods is the strategic approach of initiation – top-down or bottom-up. Similar to the central decision-making, the top-down approach provides an overview of the whole organization. Therefore, the activities in all departments and the vision of the company can be taken into account during the decision-making process. A bottom-up approach helps to include the detailed expert knowledge of individual departments, to identify technical restrictions and prerequisites for the project. For some projects, it is therefore beneficial to take on an initiation approach which combines both top-down and bottom-up. As an example, AC identified this method on the top-management level, and from this it derived its vision of the company. The individual departments were responsible for identifying use-cases to cut complexity in their organizational units. FC applied a similar approach. The CMT reports to the top-management and supports the individual departments during the process of identifying and conceptualizing the complexity-mastering methods.

Below are outlines of how the individual case-companies include the interrelatedness of methods in their projects to identify and conceptualize methods for mastering complexity.

As shown in Figure 21, at BA previously implemented methods were the prerequisite for implementing the TSM; the modular product structure enabled subsequent methods. Along with the modular product structure, BA implemented methods in other stages along the value chain. It adapted its value chain processes by separating plant roles within its network – one main plant and seven customizing plants. In the main plant, the standardized assembly processes were performed. The task of the customizing centers lay in the finalization of the product for the individual markets – mechanical and electronic interfaces, cables and parametrizing, as well as labeling.

The modularization approach towards the products, initiated by development engineers, led to an increase in the degree of shared components across all products. Hence, the variety within the production and assembly processes decreased. BA was therefore able to innovate its processes with respect to higher standardization and automation. The standardization of tools and assembly processes reduced the investment volume as well as the workloads of the employees. A higher degree of standardization enabled BA to automate its assembly lines.

Furthermore, to support the sales process, BA implemented a variant configurator. Based on the modular structure, the variant configurator contains knowledge regarding

the relationships of components and modules, permitting sales personnel to manage the process actively towards a standardized solution for the customer.

The modular product structure forms the basis for innovating the development processes through the TSM. Based on two modules, the whole functionality of the product is established. Each of these two modules consists of three components. This modular product structure requires detailed planning of the relationships and interfaces between the individual components. All product variants consist of standardized interfaces and dimensions. The TSM builds upon this work. The existing modular structure helps to establish the relationship knowledge of the individual components. Hence, the modular product structure is and was a prerequisite for the TSM.

Additionally, the existing IT systems need to be considered when implementing the TSM. BA operates other systems that fulfill similar tasks outside of the development department. Since the TSM is a database that combines various technologies, components, and solutions, it is necessary to avoid any redundancy in these systems. Redundancy of data in systems leads to unclear states of components and greater efforts in maintenance. Before implementation, BA will conduct a final evaluation of the existing systems to decide on a company-wide solution.

As described above, BA subsequently identified methods which were enabled through previously implemented methods. Based on a holistic perspective, as generally required in top-down or combined approaches, earlier or parallel implementing of methods might have been achievable.

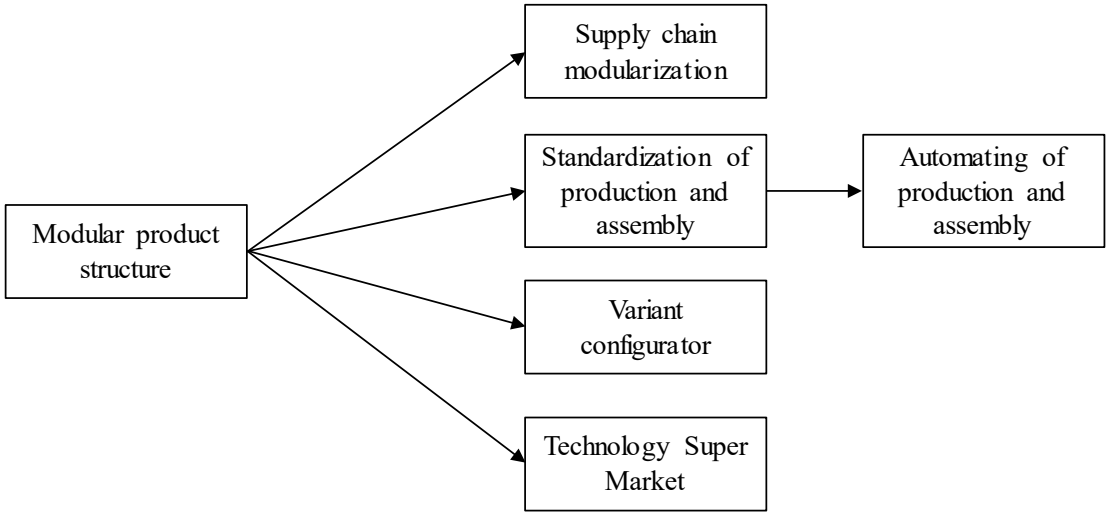


Figure 21: Interdependency of methods at BA

Until now, all SOPs have been available only on paper and in prose texts. To improve the maintenance, writing, and reviewing of SOPs, PC plans to transform all SOPs into PO-SOPs. This initiative of PO-SOPs turns the prose text SOPs into flow-chart diagrams. Each step of the flow-chart incorporates necessary detailed work instructions and related documents, so that the employee can work as efficiently as possible. Efforts to transform all SOPs into process orientation are prerequisite to PC's digitalization initiative.

One element of the digitalization initiative is the transformation of all physical into digital SOPs. Along with the digitalization of the SOPs, PC plans to optimize the IT architecture, including the introduction of digital handhelds in production. Hence, the implementation of PO-SOPs will be facilitated through the digitalization movement of the company as well.

PC applied a top-down approach to identify and conceptualize the innovative SOP architecture. The holistic perspective on the company enabled PC to identify dependencies between the digitalization approach and the PO-SOP. This permitted PC to plan the implementation of both methods in parallel.

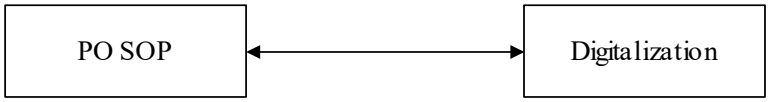


Figure 22: Interdependency of methods at PC

Since AC's approach included all departments in the product engineering process, they did not regard the interdependency between HCM and other methods, but rather within the HCM. In the past 20 years, isolated departments and individuals of AC have initiated

several projects dealing with the topic of mastering complexity. Since the interdisciplinary character of complexity along the value chain was not included in these isolated bottom-up approaches, they remained unsuccessful.

The current approach was initiated by the top-management and aimed at holistically mastering the complexity within AC. The top-management executives established the TCT to lead and drive this topic throughout the organization. The TCT, anchored with direct reporting to the top management, emphasized the mutual understanding between the individual stakeholders along the value chain. Thus, the departments identified specific methods for taking into consideration the needs and the methods of the other departments. In regular meetings, the individual methods of the departments were discussed and coordinated with the target of holistic complexity management. For example, strong interdependency existed between the departments of product development and production, procurement, and product development, as well as marketing and product development.

The various interdependencies between the methods influence their effective implementation. Since the intelligent *reuse of parts search* increases the transparency over all parts and components, it supports the implementation of *preferred series* as well as the *standardized assemblies*. Through an intelligent search mechanism, including master data and 3D shapes of parts and components, the *reuse of parts search* facilitates the consistent use of *preferred series* and *standardized assemblies* for developers. Additionally, the future implementation of a *modularized product structure* supports the use of the *variant configurator*. The establishment of modules with dedicated product functions and interfaces permits individualizing products offered in the *variant configurator*. Furthermore, both the *modularized product structure* and the *standardized components* contribute to reducing product complexity.

The CMT aligns the content of the complexity management approach with FC's CTO. Hence, this approach can be characterized as top-down. As a result, the methods are planned so that both the *variant configurator*, and *the reuse of parts search* can be implemented concurrently. Furthermore, the individual method projects include experts from the individual departments along the value chain. Therefore, FC applies a combination of a top-down and bottom-up approaches.

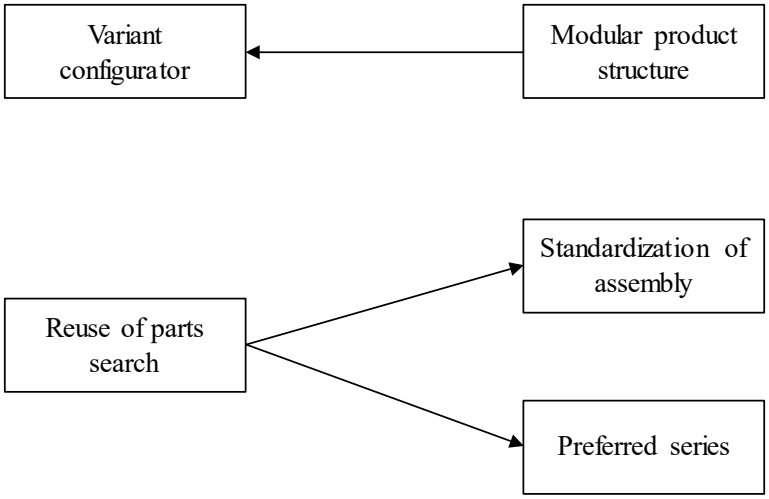


Figure 23: Interdependency of methods at FC

AI established a 'methods team' with an integrated view of the whole organization. The 'methods team' initiated the *modular product structure* with a holistic perspective on the organization. Parallel to implementing *modular product structures*, AI emphasized the *standardization of the production and assembly processes*. While the developers innovated the entire product structure, the requirements of the production served as an additional perspective. The production employees stated high process variance as a challenge for fulfilling their tasks. A higher degree of standardization of parts across all products would help to decrease the number of tools to mount them. Therefore, a close relationship between the implementation of the *modularization of the product structure* and the *standardization of the production* was identified. The parallel implementation of both methods resulted in higher efficiency in product development and production processes.

As a result of the modularization approach, AI's product structure was based on independent modules with standardized interfaces. This product structure facilitated the outsourcing of development activities and production. Hence, along with the modularization, the share of outsourcing of development and production activities to suppliers increased. To develop contracts with suppliers, the requirements of the products needed to be clearly defined. Therefore, transparency of the requirements on all levels, along with their relationships to the customer requirements, facilitated efficient outsourcing of activities and therefore increased the benefits of modularization.

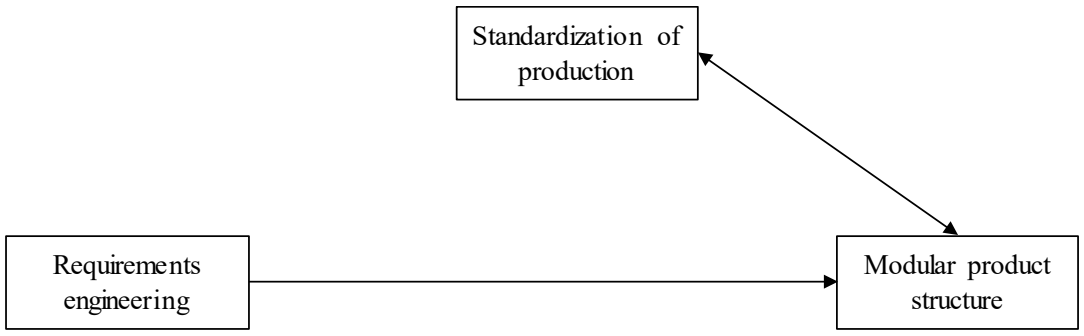


Figure 24: Interdependency of methods at AI

4.7.2.6 Interdisciplinary project teams and organizational anchoring

Complexity within manufacturing companies has many facets and is interlinked among various departments. Therefore, interdisciplinary project teams and organizational anchoring are essential factors in identifying and conceptualizing methods for mastering complexity. Additionally, in the case of dedicated project teams, integration into the organizational structure after the implementation of the method is important for the success of the method. The team members are sensitized to the topic and gain detailed knowledge regarding the methods which should be leveraged within the organization.

All case companies in this study included various stakeholders along the value chain, to identify and conceptualize their methods. The way the case-companies organized the project teams differed, though. At BA, no dedicated project team was established to conceptualize the TSM. The work for the TSM project needed to be done parallel to their daily tasks. Furthermore, the interdisciplinary employees were only occasionally involved in the project. To identify and conceptualize its modular product structure, BA initiated an interdisciplinary project team. PC, AC, FC, and AI initiated a project team to support their departments in their projects, in order to identify and conceptualize methods for mastering complexity.

If a dedicated project team was established during the projects, it needed to be integrated into the organizational structure afterward. FC and AI created a dedicated “methods team”, or “CMT”, to assist in identifying suitable methods and the conceptualization phase. Even after the implementation of the methods, these teams were planned as ongoing elements in the organization to support cross-boundary work. AC, PC, and BA, in their projects regarding modular product structure, established temporary interdisciplinary project teams. After implementing the methods, the team members were integrated into the various current organizations.

A description now follows of the individual cases with respect to the element of interdisciplinary project teams and organizational anchoring.

BA created an interdisciplinary project team to innovate its product structure. The team consisted of development engineers from different product functions, along with production engineers. In time, additional stakeholders were added to the team. After two years, BA dissolved the team and integrated the team members into the initial organizational structure. BA did not implement a comprehensive team to survey the modularity targets across the divisions. The team leader of each division surveyed the targets of the modular product structure. The company informant stated that creating an independent team controlling the targets would have led to higher target achievement than the chosen option of integrating tasks into the existing divisions. The team leaders of the divisions were responsible for coping with goal conflicts regarding the development projects and the complexity measurements. In these goal conflicts, the team leaders deprioritized the complexity targets with respect to the targets of the development projects. Thus, BA did not pursue its complexity targets in this case.

The project team for the TSM consisted of developers, top management executives, and external stakeholders. To conceptualize the TSM, BA's project team tried to schedule the efforts parallel to their daily work routine. However, while working on the TSM, the daily projects still required time and effort on the part of the project partners. Because of deadlines and customer expectations, the daily projects were more highly prioritized, compared to the project. As a result, the time invested in the TSM project was very short. To assure efficient and effective conceptualization and, eventually, implementation methods, the project members require sufficient time. An organizational change, establishing temporary, interdisciplinary project teams to plan, identify effort and benefits for mastering complexity would help to solve this problem.

SOPs influence the entire value chain of PC, therefore affecting the daily work of various stakeholders. The task of innovating the SOP architecture requires interdisciplinary perspectives. Furthermore, generating innovative ideas is an iterative process, which consumes time and effort. Operative projects dominate the daily work of employees and leave very little room for creative work. Hence, to pursue the innovative task of creating a process-oriented SOP architecture efficiently and effectively, temporary interdisciplinary project teams are beneficial.

PC created a dedicated project team consisting of quality managers of the corporate quality department. The project team involved interdisciplinary stakeholders on

corporate and site levels. On the corporate-level, the head of quality management and the quality heads of the four divisions participated in the project. On site-level, PC interviewed the site heads, top-management executives responsible for the production and supply chain, production workers, production managers, and planners, along with development engineers.

To identify and conceptualize methods for mastering complexity within the organization, AC embedded an interdisciplinary project team. The TCT consisted of stakeholders taken out of the departments along the value chain. The TCT team members were set free from any obligations in AC's daily operations, to have time and resources for innovating the complexity management. This interdisciplinary character helped to align the requirements from different perspectives to conceptualize a holistic solution along the value chain.

AC plans to split up the TCT after the project duration of three years and integrate them into all the project management teams of the product units and the departments along the product engineering process. These stakeholders will be responsible for pursuing the targets of mastering complexity.

To identify the complexity drivers along the value chain, and to identify and conceptualize methods, FC embedded a dedicated team, the CMT. The CMT is organizationally anchored as an executive department under the Chief Technology Officer (CTO). As a result, the CMT is not obliged to take on tasks regarding daily operations and has time to focus on identifying and conceptualizing innovative methods along the value chain. The company informant rates this organizational structure as a key to achieving results in complexity management. FC created a permanent division to identify suitable methods for mastering complexity. While this present study was being written the development of the organizational structure within FC, following the implementation of the methods, could not be investigated. The informant stated that the team was still facing the challenge of identifying and conceptualizing complexity-mastering methods.

AI embedded a dedicated 'methods team' to identify and conceptualize solutions for increasing efficiency and effectiveness within the organization as a whole. The interdisciplinary methods team carried out data collection via interviews and questionnaires to identify challenges and solutions. Anchored as an executive department, the 'methods team' is not burdened with tasks in daily operations and therefore focuses on the derivation of methods to support the departments. AI

established a dedicated project team to conceptualize both methods. After implementing the standardized production structures, a regular meeting every three months was held to keep track of the developments in this topic in the departments. Based on these meetings, which were led by the methods team, common cross-departmental projects were identified.

In the case of the requirements engineering project, AI also established a dedicated team. At the time of the interview with the company informant, the project was not finished yet. Hence the integration in the organizational structure could not be analyzed. The informant stated that AI planned to keep the team as a department in the organizational structure.

4.7.3 Conclusion

Summing up, the cross-case analysis showed that there are some similarities and differences among the five case companies within the process of identifying and conceptualizing methods for mastering complexity. This present study identified six common elements – *stakeholders, complexity drivers, technical characteristics, strategy, interdependency of methods, and temporary project teams* – in all case companies. The differences became evident after analyzing how the companies included the elements in their projects of identifying and conceptualizing methods.

4.8 Conclusion and summary

Five case companies were analyzed above. The within-case analysis identified methods for mastering complexity and related complexity drivers. Based on the results of the cross-case analysis, subchapter 4.7 identified six influencing factors for identifying and conceptualizing methods for mastering complexity.

In comparing the relationships of the complexity drivers and the methods in the case studies, the literature analysis and the quantitative study show some overlaps (see Table 34 below).

The complexity driver *variety of products* is described in the literature as related to the method *modularity of products.* Equally, we identified a high variety of products at BA and FC as reasons for implementing the *modular product structure*.

Three overlaps in relationships between the complexity driver *variety of customer requirements* and methods for mastering complexity can be found in the literature and

this dissertation's case studies. The *variety of customer requirements* is a relevant factor at BA and FC for implementing *modular product structure*; the literature describes a dependency between the two factors. Furthermore, AI implemented *requirements engineering* as a reaction to a high variety of customer requirements, which is also reflected in the literature.

The complexity driver *legal factors* and the method *requirements engineering* were significantly correlated in this present dissertation's quantitative study. AI named the *legal factors* as the influencing factors in implementing *requirements engineering*. Additionally, *dynamism of product technologies* and *requirements engineering* is described as interrelated in the literature and at AI.

Dynamism of product technologies is interrelated with the method *RE* in literature. Equally, at AI, *RE* was implemented to lower the effects of dynamism of product technologies. The driver *product structure* was significantly negatively correlated to the method *RE.* Also, at AI, the product structure was considered challenging in implementing *RE*, as the effort to understand the interrelationships of the requirements in the entire product structure is immense. Nevertheless, once the product structure has been analyzed and the requirements interlinked, *RE* has positive impacts on the projects.

One reason for the differences in the relationships and the selection of the methods throughout the cases lies in the additional five identified influencing factors, which play important roles in the process of identifying and conceptualizing methods for mastering complexity. It is not enough to analyze the complexity drivers of a manufacturing company to identify complexity-mastering methods. The information gained through analyzing and understanding the complexity drivers lays the foundation for identifying and conceptualizing methods for mastering complexity.

Furthermore, at this point it can be concluded that the methods at the case companies are different from the final selection through the funnel model in subchapter 2.6.2. This underlines the dependency on various influencing factors and the individuality of each company for selecting methods for mastering complexity.

The next subchapter proposes a process model to identify and conceptualize methods for mastering complexity incorporating the influencing factors. It builds upon the insights gained in this and previous subchapters.

Table 34: Overview of relationships between complexity drivers and methods in literature, quantitative study, and cases

		Complexity Drivers							
Case Company	**Method**	*Variety of products*	*Variety of customer requirements*	*Legal factors*	*Number of products*	*Dynamics of product technologies*	*Dynamics of production technologies*	*Variety of production & supply chain processes*	*Others*
BA	*TSM*	•	•	•	•				
	MPS	• *	• *		•			•	
PC	*PO-SOP*	•	•	•	•	•	•		
AC	*HCM*	•	•		•	•	•	•	Organizational structure
FC	*Standardization of assemblies*	•			•				
	Preferred series	•			•			•	Number of suppliers, product structure
	Reuse of parts search	•			•			•	
	Variant configurator	•			•			•	
	Modularity of products	• *	• *						Organizational structure
AI	*Standardization of production*	•			•			•	
	RE	•	• *	• **		• *	•		Product structure**, Dynamics of competition

*the literature identified the same correlation; ** the relationship was also identified in the quantitative study

5 Process model for mastering complexity

The concept underlying this dissertation's model has already been published as an initial study by Kohr, Ahmad, Alkan, Chinnathai, Budde, Vera, Friedli, and Harrison: *"Proposing a holistic framework for the assessment and management of manufacturing complexity"* (Kohr et al., 2018). It describes the concept of the model, focusing on integrating human and data-centric information to identify and conceptualize methods for mastering complexity.

Chapter 5 uses the results from Chapters 3 and 4 to create a process model to support manufacturing companies in identifying and conceptualizing methods for mastering their complexity. In this chapter the common influencing factors described in subchapter 4.7 will be elaborated on and integrated as elements in the process model. This dissertation's theoretical foundation, based on the contingency and the STS theory, has supported the research process.

The contingency theory mainly provided a basis for analyzing the elements *complexity drivers* and *interdependency of the methods*. Based on the STS theory, four elements were included in the process model – *characteristics of products and processes, strategy*, *interdisciplinary project teams*, and *stakeholders*. Thus, the model jointly optimizes the needs of the stakeholders with the technical characteristics of the products and processes.

Cherns (1976, 1987), Clegg (2000) and Closs (2008) derived several principles for achieving synergy between a company's technical and social systems. However, a process model for supporting companies in achieving a substantial consideration of these principles in their design of complexity management has not yet been published. The present dissertation proposes a process model which integrates most principles, to help companies in designing complexity management measures more efficiently, by considering and integrating technical and social aspects concurrently.

Table 35 describes the design principles of socio-technical systems and outlines how the process model takes these principles into account.

Table 35: Socio-technical principles fulfilled by the process model

Socio-technical systems principles	***Source***	***Supported by the model***
Boundary location	Cherns (1976, 1987); Closs (2008)	Involving the elements s*takeholders, interdisciplinary project teams,* and *dependency of methods* permits an elimination of obstacles to knowledge- and information-sharing, as well as organization-wide learning.
Compatibility	Cherns (1976, 1987); Closs (2008)	The model incorporates various elements along the process of identifying and conceptualizing methods for mastering complexity. The model promotes aligning methods with the target of mastering complexity.
Design is an extended social process	Clegg (2000)	The extended social process is taken into account through iterative cycles of identifying, conceptualizing and re-evaluating methods for mastering complexity.
Design is contingent	Clegg (2000)	Contingencies are taken into account by integrating *characteristics of products and processes, strategy, complexity drivers, stakeholders,* and *interdisciplinary project teams*. These various perspectives support the process of identifying and conceptualizing complexity-mastering methods.
Design is socially shaped	Clegg (2000)	The model incorporates social factors through the elements *stakeholders* as well as *interdisciplinary project teams* and should, therefore, allow for evaluating their influence on the methods for mastering complexity.
Design is systemic	Clegg (2000)	The model creates transparency regarding the interdependencies of various stages along the value chain by integrating *characteristics of products and processes, stakeholders,* and *interdisciplinary project teams.*
Design should reflect the needs of the business, its users, and their managers	Clegg (2000)	By integrating *characteristics of products and processes, complexity drivers, stakeholders*, and *interdisciplinary project teams*, the model accounts for alignment of business, user and manager needs.
Incompletion	Cherns (1976, 1987); Closs (2008)	The model helps to monitor changes in the organization by integrating various elements. Therefore, the methods' suitability for the individual needs of the organization can be evaluated.
Information flow	Cherns (1976, 1987); Closs (2008)	The process model serves as a structure for gathering and analyzing relevant data to provide necessary information to responsible persons.

Table 36: Socio-technical principles fulfilled by the process model (continued)

Socio-technical systems principles	***Source***	***Supported by the model***
Minimal critical specification/ Design involves making choices	Cherns (1976, 1987); Clegg (2000)	The model includes multi-dimensional perspectives to evaluate identifying and conceptualizing methods for mastering complexity.
Multifunctional principle	Cherns (1976, 1987); Closs (2008)	The model element *interdisciplinary project teams* supports fostering the expansion of people's roles within the organization.
Power and authority	Cherns (1976, 1987); Closs (2008)	The model takes into consideration the *organizational anchoring of interdisciplinary project teams and stakeholders*, to guarantee access to information and to provide the means to implement methods for mastering complexity.
Support congruence	Cherns (1976, 1987); Closs (2008)	By including different perspectives of the organization, its people and complexity drivers, the model supports the alignment towards the common target of mastering complexity Socio-technical systems principles by Cherns (1976, 1987).
Transitional organization	Cherns (1976, 1987); Closs (2008)	The model supports the transition of an organization through integrating elements and designing a process flow for identifying and conceptualizing methods suitable for the individual characteristics as well as the needs of the organization.
Values and mindsets are central to design	Cherns (1976, 1987); Clegg (2000)	The model incorporates *characteristics of products and processes,* e.g., technologies as well as *stakeholders* and *interdisciplinary project teams*. As a result, the model supports the coordination of humans and technologies to foster complementary skills and abilities.
Variance control	Cherns (1976, 1987); Closs (2008)	The model incorporates elements which foster the inclusion of different organizational units into the process, helping to prevent exportation of variances from one organizational unit to another.

Figure 25 shows the process model for identifying and conceptualizing methods to master complexity in the manufacturing industry. The process model integrates the six elements *complexity drivers, interdependency of the methods, characteristics of products and processes, strategy, interdisciplinary project teams*, and *stakeholders*. The process model's structure consists of four phases:

- First, the *complexity drivers* are measured to identify primary areas to apply methods.
- Second, the *internal analysis of the characteristics* of the company, its *products and processes*, as well as the *strategic orientation*, forms the basis for evaluating the suitability of methods.
- Third, this information is integrated to identify an *initial list of methods for mastering the complexity*.
- Fourth, the elements of *interdisciplinary project teams and organizational anchoring*, *stakeholders*, as well as *interdependency of methods* aim at prioritizing and conceptualizing the methods.

The methods for mastering complexity should be constantly reviewed and brought into line with the elements of the company. Therefore this model is designed as an iterative process.

In the following subchapter 5.1 the elements of the process model are described. Subchapter 5.2 elaborates on an application of the process model at a company from the medical technology industry.

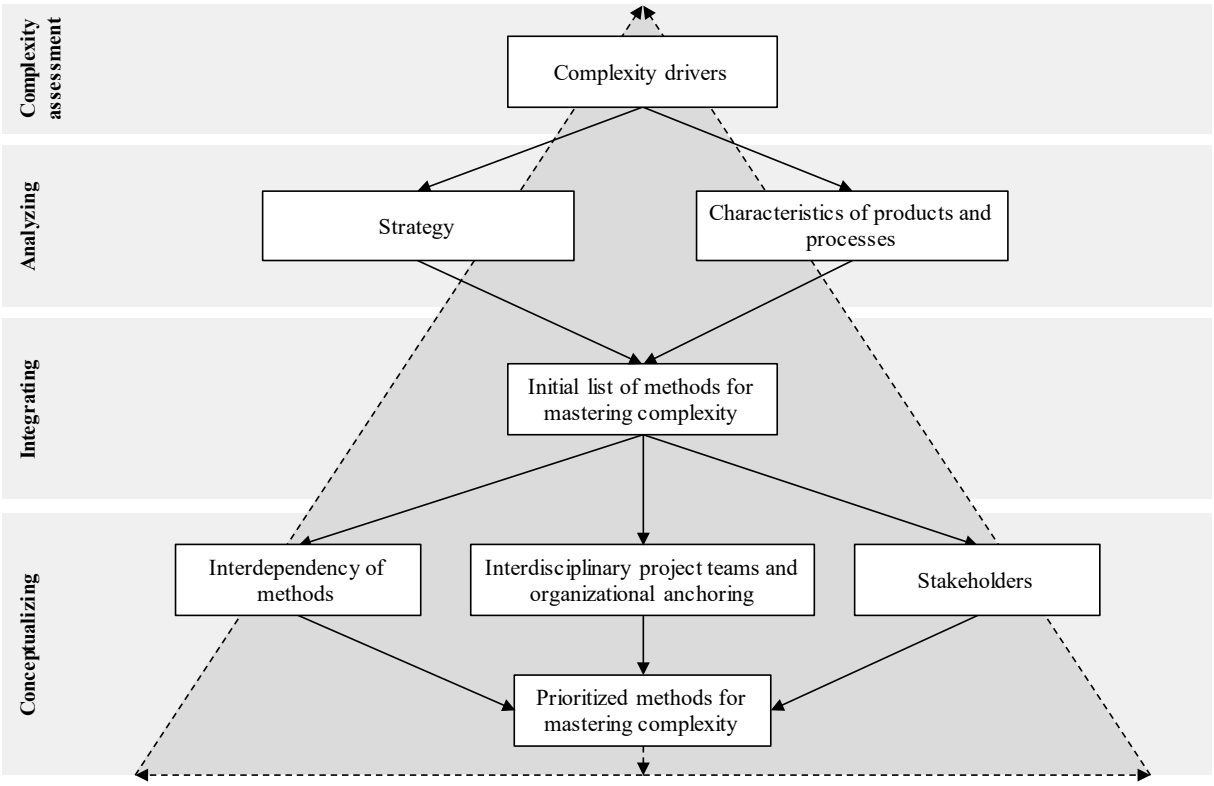


Figure 25: Process model to support identifying and conceptualizing methods for mastering complexity

5.1 Elements of the process model for mastering complexity

The following subchapters will describe the elements of the process model. The description will include relevant literature regarding the elements, and guidelines for incorporating them into the process of identifying and conceptualizing methods for mastering complexity.

5.1.1 Complexity drivers

In this subchapter the *complexity assessment* to identify the complexity drivers is described (see Figure 26).

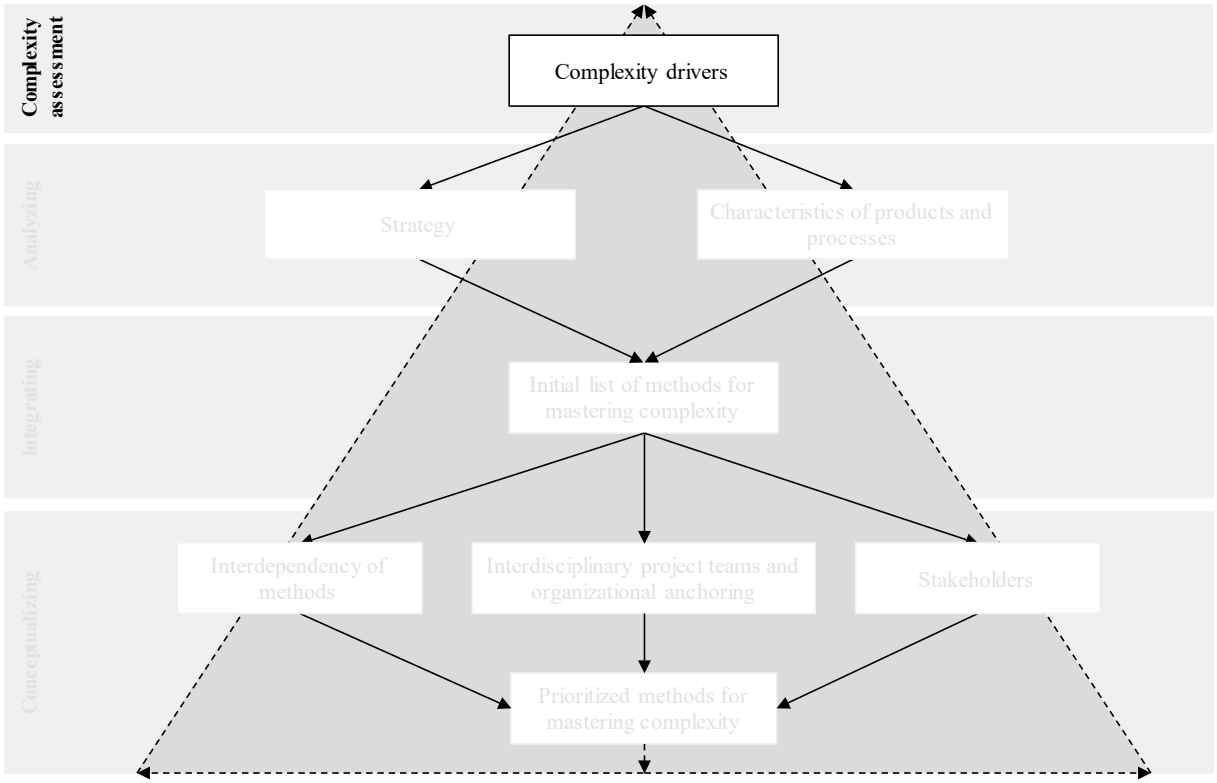


Figure 26: Process model – Element 1: Complexity drivers

Complexity drivers are suitable for identifying the complexity of an organization. Two of the cases (FC, PC) in this study initially analyzed complexity drivers in detail, including their influence on the efforts within processes. AI and AC measured individual KPIs to track the levels of complexity and their increase. This is in line with research since many authors describe the relevance of obtaining an overview of the complexity drivers for mastering complexity (Heydari & Dalili, 2012, p. 64; Serdar-Asan, 2013, p. 534; Vogel & Lasch, 2016, p. 13). BA, on the other hand, perceived an increase in the general complexity without analyzing the drivers and their effects on the organization.

Complexity drivers are related to various stages along the value chain. In subchapter 2.4, clusters of complexity drivers were described based on a literature review by Vogel and Lasch (2016). An analysis of the complexity drivers along the value chain of an organization is crucial to determine methods for mastering them.

Subchapter 3.5 identified the relevance of complexity drivers in the manufacturing industry, and their underlying structure. Based on a study with 130 participating companies from the manufacturing industry, *variety of products, variety of customer*

requirements and *number of customers* were identified as the most relevant complexity drivers.

Furthermore, the analysis in subchapter 3.5.2 of the underlying structures indicated six clusters of complexity drivers which need to be managed within manufacturing companies. This clustering of complexity drivers enables companies to gain an overview of their complexity and to determine actions efficiently. The cross-case analysis identified the analysis of the complexity drivers' as the initial step towards ascertaining methods for mastering the company's complexity. The identified drivers at the case companies were in line with the six clusters of complexity drivers. Additional complexity drivers were also singled out at the companies.

Further elements in the process model for identifying and conceptualizing methods will now be described.

5.1.2 Strategy

In this subchapter the element *strategy* is described. It is one out of two elements in *phase 2 – analyzing (*see Figure 27).

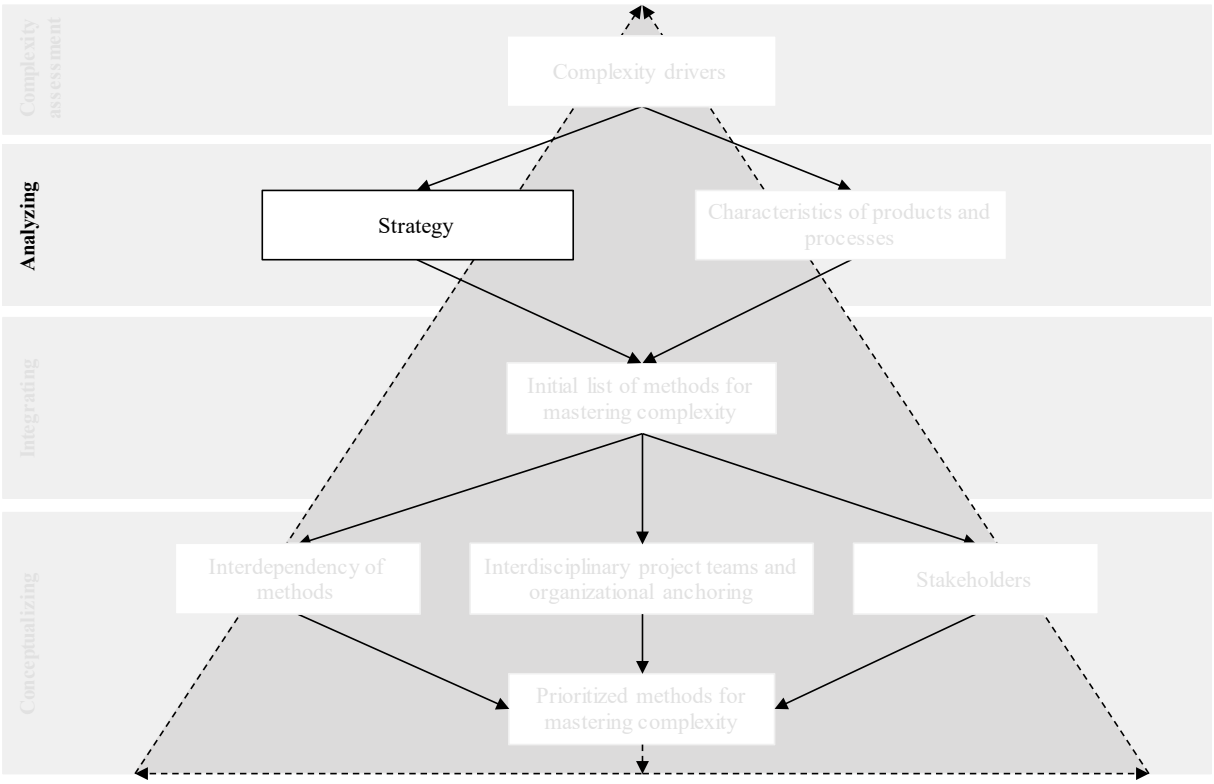


Figure 27: Process model – Element 2: Strategy

Strategy is defined as “a pattern in a stream of actions” (Mintzberg, 1978, p. 935). Hence, strategy aims at establishing both intended guidelines and a posteriori consistencies in decision-making (Mintzberg, 1978, p. 935).

Hofer and Schendel (1978, p. 27) describe three different strategies within an organization – corporate strategy, business strategy, and functional area strategy. Corporate strategy deals with different operating and group divisions, as well as separate legal business entities. On the business level, managers break down the corporate strategy into industry and product segment strategies encompassing competences and competitive advantages. On the functional level, the strategy focuses on increasing resource productivity. Hofer and Schendel (1978, p. 29) emphasize the importance of aligning the three levels of strategy for being successful over time. (Hofer & Schendel, 1978, pp. 27–29)

Since the model in this present dissertation emphasizes the process of identifying and conceptualizing of methods along the entire value chain, the following subchapters describe the individual functional area strategies of manufacturing, product, marketing, and supply chain, together with their interrelationships.

5.1.2.1 Manufacturing strategy

Skinner (1969) describes manufacturing as a competitive lever for achieving corporate success. Beneficial effects on the organization’s success can be expected due to the aligning of manufacturing strategy with business strategy (Kotha & Orne, 1989; Skinner, 1969, p. 138). To formulate a manufacturing strategy, manufacturers first need to define competitive priorities based on their business strategy. Since competitive priorities establish the strategic focus for developing specific manufacturing capabilities, Boyer and Lewis (2002) regard competitive priorities as a central decision variable for manufacturers. Second, the competitive priorities guide the strategic choices regarding structural and infrastructural decisions (Koufteros et al., 2002). Third, manufacturers achieve competitive capabilities through strategic choices (Flynn & Flynn, 2004; Rosenzweig & Easton, 2010). Rosenzweig and Easton (2010) regard competitive capabilities as the abilities to compete with respect to quality, flexibility, delivery, and costs in a market.

No universal definition of manufacturing strategy can be found in the literature reviewed. Based on existing definitions, the manufacturing strategy is referred to as a series of decisions over time to allow an organization to establish a manufacturing

structure and infrastructure as well as to develop internal capabilities (Deflorin, 2007, p. 16; Hayes & Wheelwright, 1984).

5.1.2.2 Product strategy

New product strategy is considered as a relevant component of the overall corporate plan. The elements of a new product strategy comprise the individual products, markets, technologies, and the nature of the process. R. G. Cooper (1983, p. 247) characterizes the product strategy of an organization by the elements of product synergy, product focus, differential advantage, and types of products developed. The market dimensions comprise market size, growth, and potential, as well as the competitive situation and the market newness to the firm (R. G. Cooper, 1983, p. 245). The new product strategy of an organization can also be described by the orientation of the new product program, with decisions regarding the sources of new product ideas, technical and market orientation, and the level of R&D spending (R. G. Cooper, 1983, p. 245).

Pehrsson (1995) describes international product strategies and differentiates between a standardization approach across market segments and product adaptation to market segments. He characterizes a full standardization approach as offering identical products to various market segments. On the other hand, the full adaptation approach implies a total absence of shared elements across the product line and individualizing products to regional requirements. (Pehrsson, 1995, pp. 237–238)

Product strategy represents the future degree of product adaptation on markets and thus can be described as an essential input for identifying methods for mastering complexity. BA, for example, maintains it can fulfill every customer demand, and therefore requires high flexibility in product and production structure. As a result, BA has implemented the MPS and TSM for mastering its complexity.

5.1.2.3 Marketing strategy

Marketing is a set of activities which ensure that the company's products fulfill the customer's needs (American Marketing Association, 2013; Fifield, 2007, p. 1). However, there is no universal definition of marketing strategy in all of the literature the author of this dissertation has reviewed.

Fifield (2007) stresses the importance of the link between business strategy and marketing strategy. According to him, marketing strategy translates the business strategy and its objectives into marketing activities. He defines marketing strategy as

"the process by which the organization aligns itself with the market it has decided to serve" (Fifield, 2007, p. 16). His marketing strategy consists of seven elements.

- First, the organization segments the market and decides which segments should be targeted;
- Second, the organization identifies the customer value, meaning the needs of the customer, and transfers them into the offerings of the organization;
- Third, the organization needs structures regarding processes and culture;
- Fourth, activities for customer retention need to be identified;
- Fifth, the organization must identify unique positions in markets by combining positioning and branding;
- Sixth, the organization identifies the industry and market they want to be present in;
- Seventh, the value proposition brings together the knowledge about the market, customers, and the competition, and states the basis for the offerings of the organization. (Fifield, 2007, pp. 131–133)

The market strategy is relevant for manufacturing companies to identify and conceptualize methods for mastering complexity, as it delivers the basis for product portfolio decisions. The product portfolio and the offered product variants are relevant driver categories in our statistical analysis, as they are in the case companies.

5.1.2.4 Supply Chain Strategy (SCS)

Stevens (1989) emphasized the importance of integrating the supply chain to solve the conflicts within an organization's functions. Many authors describe the relationship between of SCS and other functions within an organization.

Fine (2000) describes the relationship between SC and products and suggests designing them simultaneously. The demand for products changes during their product lifecycle stages (Aitken et al., 2003, p. 138). These authors maintain that the product lifecycle impacts the SCS and requires the SCS to change, to uphold the organization's competitiveness. Novak and Eppinger (2001) describe the relationship between product complexity and the design of an SC, specifically vertical integration. SCS is related to

marketing (Jüttner et al., 2010; Mentzer et al., 2008), production (Mentzer et al., 2008), and operations (Perez-Franco et al., 2016).

Narasimhan et al. (2008, p. 4) regard SCS as "the pattern of decisions related to sourcing products, capacity planning, conversion of raw materials, demand and services". The authors stress the importance of linking the SCS to the overall business strategy as the decisions in SCS affect core business processes regarding production and distribution of products. Therefore, the overall business objectives serve as a basis for deriving strategic targets for managing the supply chain. As a consequence, SCS should be an integral part of the process for identifying and conceptualizing complexity-mastering methods. (Narasimhan et al., 2008, p. 4)

The production processes of all case companies are globalized. Hence the supply chain strategy is a vital factor for managing complexity. BA's supply chain strategy, for example, maintains a close collaboration with suppliers. Therefore, BA includes suppliers in conceptualizing the MPS and the components' subsequent outsourcing.

5.1.3 Characteristics of products and processes

The second element of *phase 2*, *characteristics of products and processes*, is described in this subchapter (see Figure 28).

The element *complexity drivers* describes the importance of identifying the different levels of complexity along the value chain. This manifestation of complexity indicates a first working point for managers to increase efficiency within an organization. To decide on methods for handling this complexity, more in-depth knowledge of the organization is required. The characteristics of the products and the processes along the value chain help to evaluate the suitability of these methods. The dimensions of the product, the processes along the value chain, and their manifestations in manufacturing companies are outlined in this subchapter (see Figure 28).

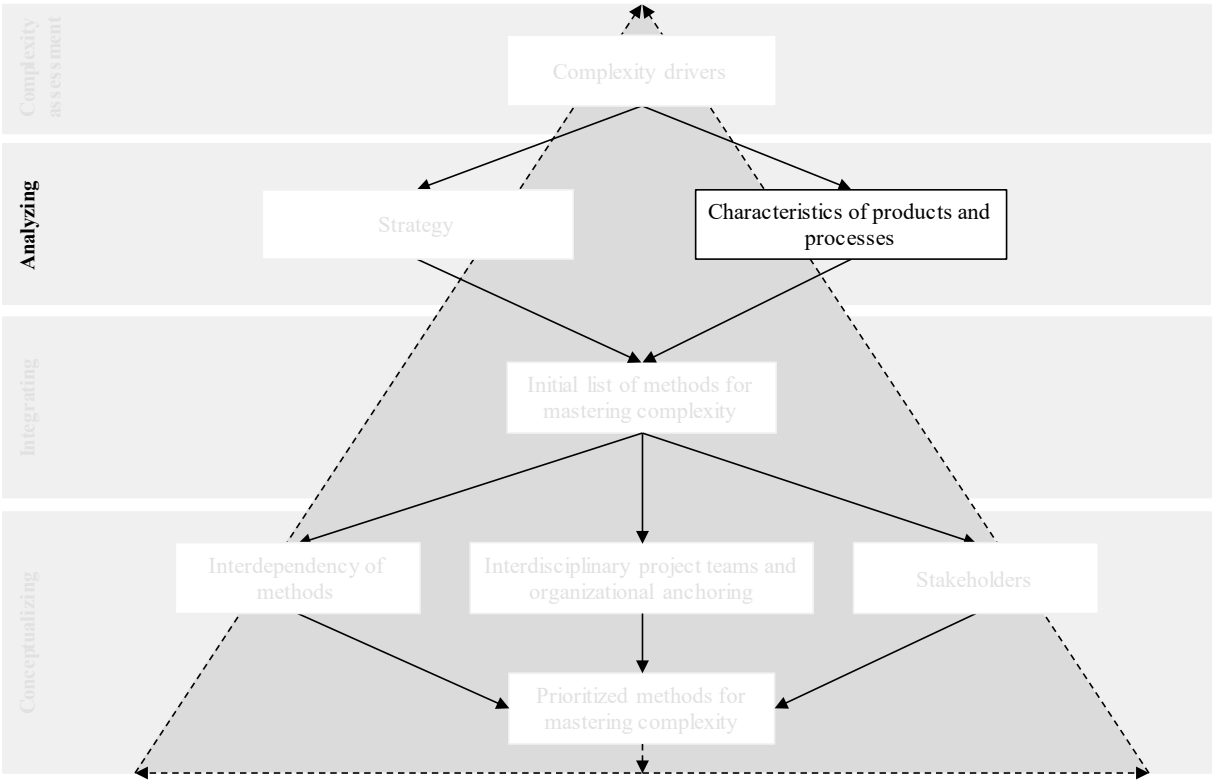


Figure 28: Process model – Element 3: Characteristics of products and processes

Fisher (1997) and Lee (2002) identified a product classification with regard to its demand patterns – functional and innovative. Each demand pattern can be characterized along the dimensions product life cycle, product variety, demand predictability, and standards for lead times. Functional products comprise staple products like groceries, retail, or fossil fuel products. Their demand is very predictable, and the products fulfill customers' basic needs with low product variability. Innovative products are characterized by volatile demand and therefore require high product variety. While the contribution margin for innovative products is relatively high (20%-60%) the lead time should be very low (1 day to 2 weeks). In contrast, functional products only contribute marginally, from 5% to 20%, and their lead time ranges from six months to one year. (Fisher, 1997, pp. 106–107; Lee, 2002, p. 106)

White and Prybutok (2001), and Hayes and Wheelwright (1984) characterize production processes along ten dimensions: material requirements, scheduling, production runs, setups, type of equipment utilized, inventory levels (Raw, WIP, finished goods), variety of products, worker skill level, worker job content (scope) and control over suppliers. They distinguish between two extremes regarding the type of production processes – non-repetitive and repetitive production – as shown in Table 37 (White & Prybutok, 2001, p. 116).

Table 37: Characteristics of production processes (Hayes & Wheelwright, 1984, p. 180; White & Prybutok, 2001, p. 116)

	Production processes	
Characteristics	*Non-repetitive*	*Repetitive*
Variety of products	customized	standardized
Material requirements	difficult to predict	very predictable
Scheduling	uncertain, frequent changes	fixed schedule, inflexible
Production runs	short	long
Setups	different every job	very few and costly
Type of equipment utilized	general purpose	special purpose
Worker job content (scope)	large	small
Worker skill level	high	low
Control over suppliers	low	high
Inventory levels		
Raw	low	high
WIP	high	low
Finished goods	low	high

Skinner (1969) (Figure 20) adds important trade-off decisions in manufacturing, with respect to plant and equipment, production planning and control, labor and staffing, product design and engineering, as well as organization and management (Skinner, 1969, p. 141).

Decision areas	*Decision*	*Alternatives*
Plant and equipment	Span of process	Make or buy
	Plant size	One big plant or several smaller ones
	Plant location	Locate near markets or locate near materials
	Investment decisions	Invest mainly in buildings or equipment or inventories or research
	Choice of equipment	General-purpose or special-purpose equipment
	Kind of tooling	Temporary, minimum tooling or production tooling
Production planning and control	Frequency of inventory	Few or many breaks in production for buffer stocks
	Inventory size	High inventory or a lower inventory
	Degree of inventory control	Control in great detail or in lesser detail
	What to control	Controls designed to minimize machine downtime or labor cost or time in process, or to maximize output of particular products or material usage
	Quality control	High reliability and quality or low costs
	Use of standards	Formal or informal or none at all
Labor and staffing	Job specialization	Highly specialized or not highly specialized
	Supervision	Technically trained first-line supervisor or non-technically trained supervisor
	Wage system	Many job grades or few job grades; incentive wages or hourly wages
	Supervision	Close supervision or loose supervision
	Industrial engineers	Many or few such men
Product design/engineering	Size of product line	Many customer specials or few specials or none at all
	Design stability	Frozen design or many engineering change orders
	Technological risk	Use of new processes unproved by competitors or follow-the-leader policy
	Engineering	Complete packaged design or design-as-you-go approach
	Use of manufacturing engineering	Few or many manufacturing engineers
Organization and management	Kind of organization	Functional or product focus or geographical or other
	Executive use of time	High involvement in investment or production planning or cost control or quality control or other activities
	Degree of risk assumed	Decisions based on much or little information
	Use of staff	Large or small staff group
	Executive style	Much or little involvement in detail; authoritarian or non-directive style; much or little contact with organization

Figure 29: Trade-off decisions in manufacturing (Skinner, 1969, p. 141)

With their framework that combines the concept of the product life cycle and process life cycle, Hayes and Wheelwright (1979b, 1979a) triggered research regarding aligning product characteristics with supply chain processes (Morita et al., 2015, p. 229). Their proposed framework has helped managers to adjust activities in marketing and manufacturing to cope with market developments and technologies (Hayes & Wheelwright, 1979a, p. 136).

Fisher (1997) suggests adapting the supply chain according to the type of products offered by the company. While innovative products require a "market-responsive process", functional products need a "physically efficient process" (Fisher, 1997, p. 107). Thus, companies offering innovative products should focus their investments on the responsiveness and flexibility of their supply chain to react to unpredictable demand. Targeting the lowest possible costs, companies supplying functional products need to supply predictable demand efficiently. To postpone individualization of products to the end of the value chain, companies should use modular product design for innovative products, whereas for functional products a cost minimization should be targeted. (Fisher, 1997, pp. 107–108)

S. H. Huang et al. (2002) and Vonderembse et al. (2006) researched aligning product types and life cycle stages with supply chain processes. According to their research lean supply chains are suitable for standard products, whereas agile supply chains should be applied to innovative products, as shown in Figure 30. Additionally, Vonderembse et al. (2006) investigated the relationship of product lifecycle stages with supply chain processes and observed that for innovative products in maturity and decline stages there is a shift towards lean supply chains. (S. H. Huang et al., 2002, p. 195; Vonderembse et al., 2006, pp. 228–234)

	Innovative product	Hybrid product	Standard product
Agile supply chain	+	O	-
Hybrid supply chain	O	+	O
Lean supply chain	-	O	+

+: Desired application
O: Less desired application
-: Undesired application

Figure 30: Alignment of product and supply chain types, adapted from S. H. Huang et al. (2002)

Hallgren and Olhager (2009, p. 989) align lean management with cost leadership and agile with a differentiation strategy. According to the literature statements above, the concept of aligning the product with value chain characteristics is widely accepted among researchers. One apparent example features the combination of modular product structure and point of customer individualization in the value chain (Morita et al., 2015, p. 230).

The type of product and production, as well as supply chain processes, determine the suitability of methods for mastering complexity. Thus, companies offering innovative products ought to focus on methods which increase the flexibility within their value chain, e.g., reconfigurable manufacturing systems, modular product structures. In contrast, companies offering functional products should instead focus on methods aiming at increasing the efficiency in processes or reduce the product portfolio variety.

PC's production processes are characterized as repetitive. Even though the products are innovative, in terms of the degree of novelty to the market, the products are standardized with no customer individualization. Therefore, the method implemented by PC focuses on increasing the standardization and consistency of the quality in the processes. FC, AI, AC, and BA offer more individualized, innovative products. The production processes are non-repetitive. As a consequence, their implemented methods, e.g., modularity of products and processes, increase the flexibility in production and supply chain processes.

5.1.4 Initial list of methods for mastering complexity

In *phase 3 – integrating* the initial list of methods based on the learning and insights derived from the previous elements (see Figure 31).

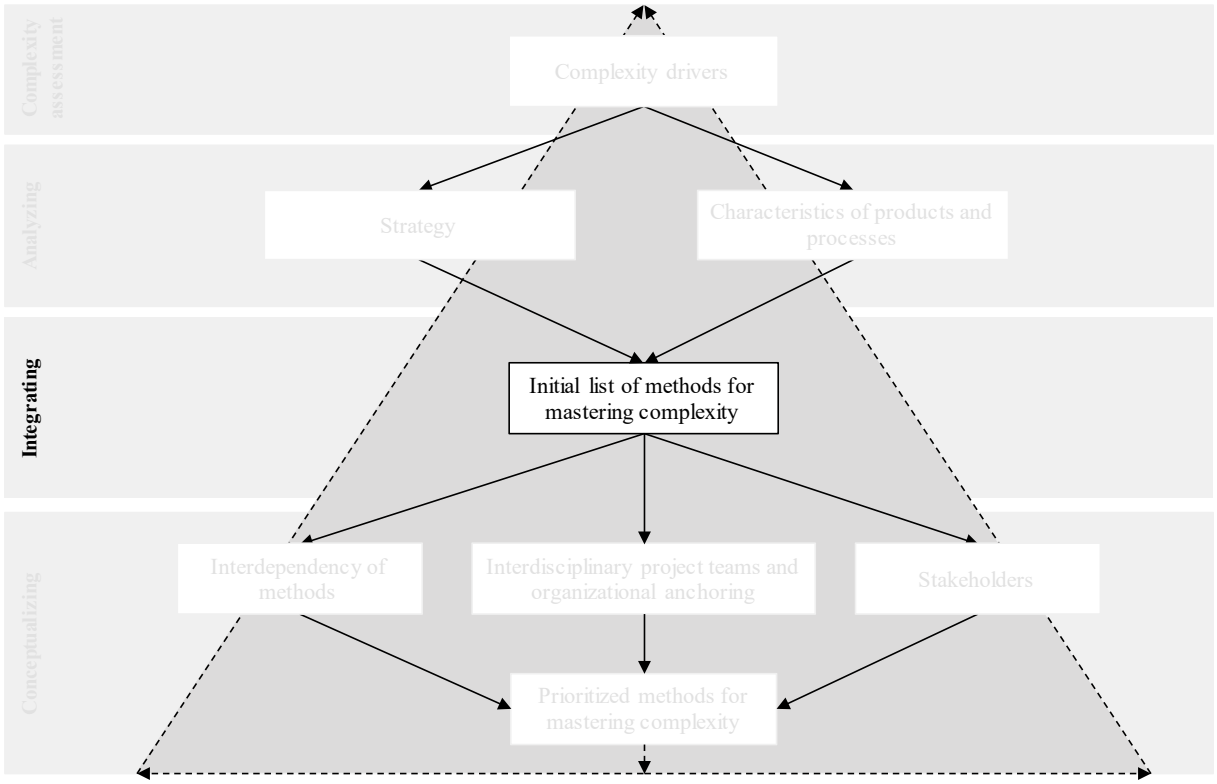


Figure 31: Process model – Element 4: Initial list of methods for mastering complexity

Creating a list of relevant methods is supported by the relationship matrix determined from literature, cases and the quantitative study of this research (see Table 34). The matrix can help manufacturing companies to identify possible methods for mastering complexity based on the complexity drivers they are facing. Furthermore, based on the significant, negative as well as positive, correlations from the quantitative study, the tendencies towards conflicting and supporting effects between methods and complexity drivers can be derived.

Table 38: Relationship matrix of complexity drivers and methods

		Methods										
Origin	***Complexity drivers***	*Product portfolio management*	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	*Technology Super Market (TSM)*	*HCM*	*Standardization of assemblies*	*Preferred series*	*Reuse of parts search*	*Variant configurator*
Factors identified from quantitative study	*Production and value chain complexity*		•	•	•/+	+		•				
	Product and market dynamics	•/+	•	•/+	•	•	•	•				
	Product and market varietv	•	•	•	•	•	•	•	•	•	•	•
	Supply uncertainty		-	-								
	Legal and political factors		+		-	•	•					
	Corporate structure and culture		•		•							
Additional complexity drivers identified from cases	*Number of suppliers*				-					•		
	Product structure		-				•	•		•		
	Number of products/parts		•		•		•	•	•	•	•	•
	Variety of production & SC processes		•				•	•	•	•	•	•

• Relationship identified from the literature & cases

+/- Relationship identified in the quantitative study

However, analyzing the complexity drivers is not sufficient for identifying and conceptualizing complexity-mastering methods within a manufacturing company. This present study's analyses showed that there is only a low to medium correlation between complexity drivers and these methods.

5.1.5 Interdependency of methods

In *phase 4 – conceptualizing* three elements incorporated to prioritize the methods for mastering complexity. The fifth *element – interdependency of methods* emphasizes the linking of different methods (see Figure 32).

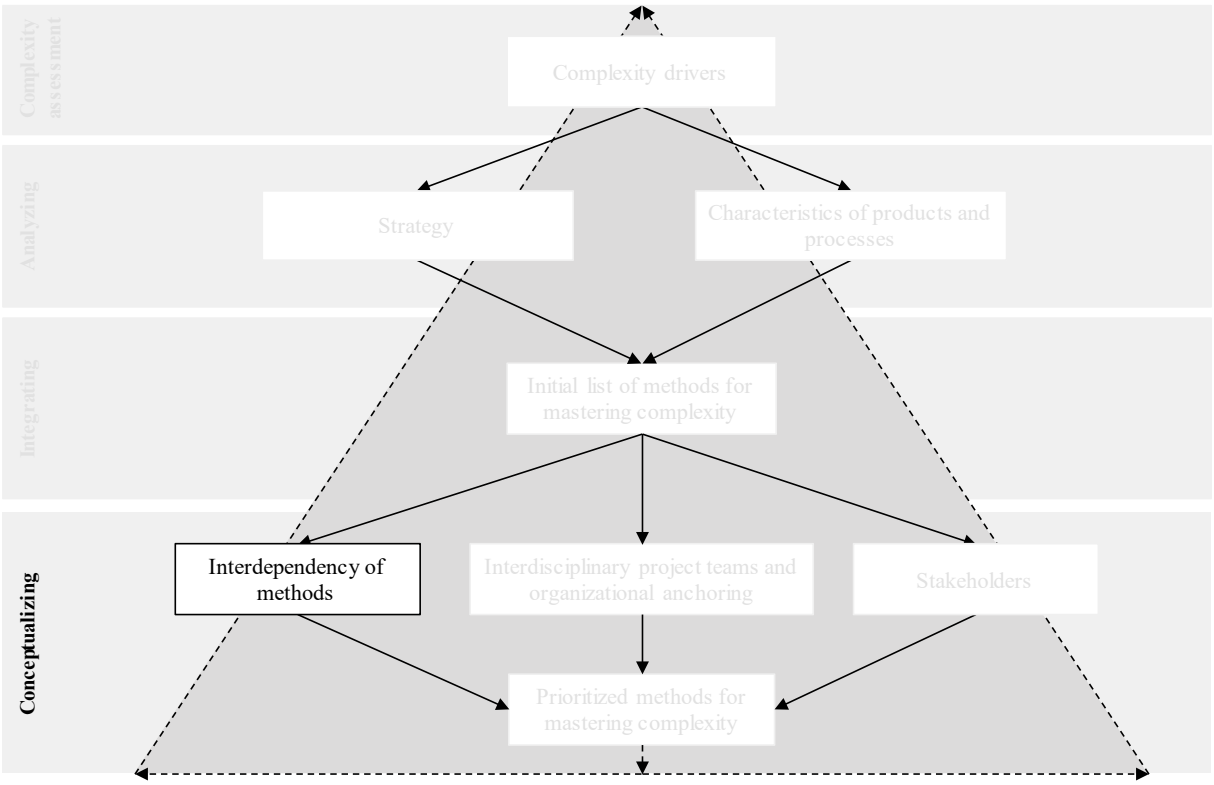


Figure 32: Process model – Element 5: Interdependency of methods

The combined effects of product and process innovation on productivity have been studied thoroughly (Lin et al., 2016, p. 143). Many authors have investigated the complementary effects of innovations along the value chain and supporting processes on company productivity.

Martínez-Ros and Labeaga (2009) studied the implementation and development of product and process innovations. They found that persistence increases the chances of innovation by between 2-4%, regarding both product and processes. Furthermore, they state that managers should consider complementarities between innovations (Martínez-Ros & Labeaga, 2009, p. 64).

Goedhuys and Veugelers (2012) researched the success of product and process innovation based on company innovation strategies. They discovered that product and process innovation contribute significantly to company growth. Furthermore, they emphasize the importance of combining product and process innovation to significantly improve firm growth. Thus, a company achieves increasing sales particularly through product innovations when it additionally introduces process innovation alongside of it (Goedhuys & Veugelers, 2012, p. 527).

T. Schmidt and Rammer (2007) emphasize non-technological innovations like the implementation of new business methods, organizational concepts or a change of business activities in an immaterial way (T. Schmidt & Rammer, 2007, p. 4). In their studies they have found that non-technological innovations only marginally affect the profit margins of a firm, compared to the strong effects of technological innovation (T. Schmidt & Rammer, 2007). Nevertheless, they maintain that non-technological innovation has a stimulating effect on the success of technological innovation through product introduction or process optimizations (T. Schmidt & Rammer, 2007, p. 32).

Similarly, Ballot et al. (2015) investigated the relationship between technological – product and process innovation – and non-technological – organizational innovation. Depending on the contingencies of the companies, they identified complementarities between process and product innovations, and between product and organization innovations. The analysis regarding these relationships was inconclusive. Applying different sub-samples showed that the contingencies national context, along with company size and capabilities, influenced the combinability of the different forms of innovation. (Ballot et al., 2015, pp. 225–227)

The literature above demonstrates that the topic of relationships between innovations along the value chain has long been thoroughly discussed. The literature describes beneficial and complementary effects achieved by introducing methods in parallel. Since every case introduced methods simultaneously, and identified possible positive effects, the case studies are in line with the literature – especially with respect to the beneficial effects of implementing non-technological methods alongside of technological innovations. FC, for example, implemented the *reused parts search* as well as *the variant configurator* alongside the *standardization of components*. Therefore this present dissertation included *interdependency of methods* in the proposed model for identifying and conceptualizing methods for mastering complexity.

5.1.6 Interdisciplinary project teams and organizational anchoring

The *sixth element - interdisciplinary project teams and organizational anchoring* takes into consideration the different perspectives of an organization for selecting methods to master complexity (see Figure 33).

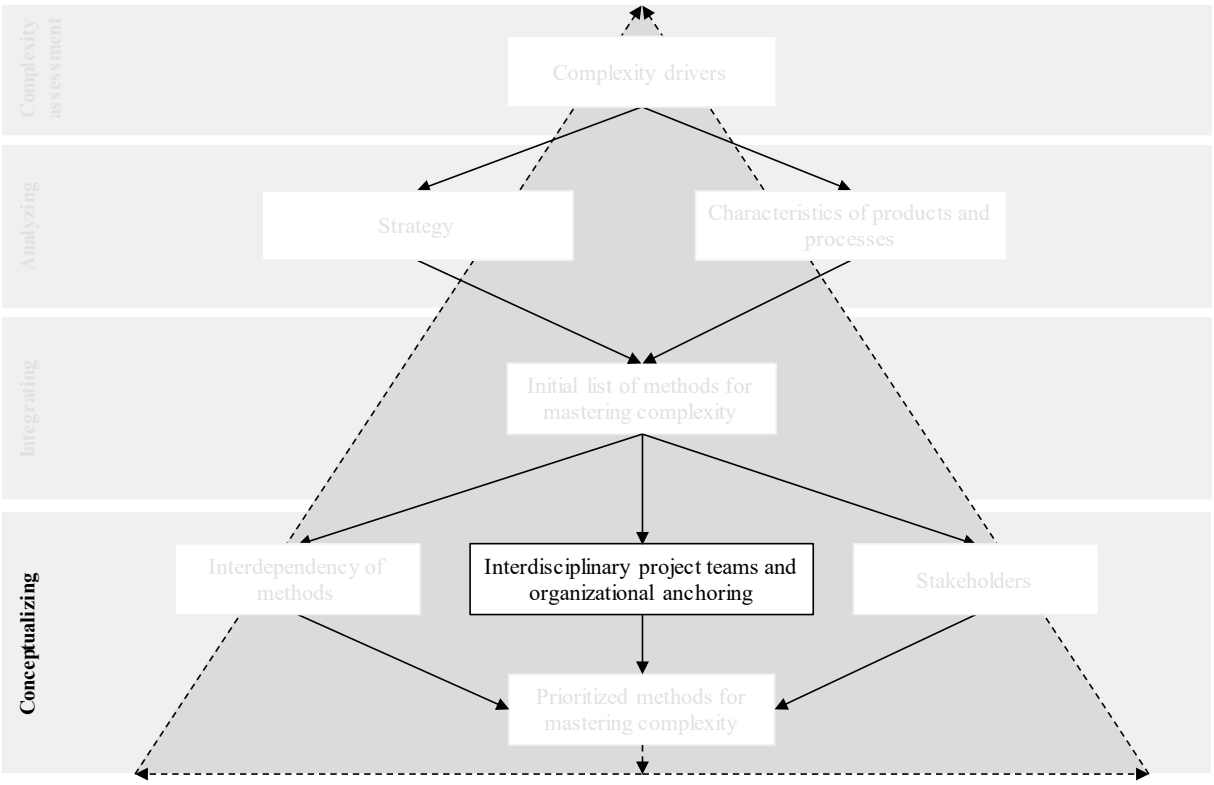


Figure 33: Process model – Element 6: Interdisciplinary project teams and organizational anchoring

Management scholars emphasize the increasing importance of temporality and time in organizational science (Ancona et al., 2001; Mitchell & James, 2001). Temporary organizational forms, e.g., projects (Grabher, 2002; Schwab & Miner, 2008), movie sets (Bechky, 2006; DeFillippi & Arthur, 1998), and task forces (Bigley & Roberts, 2001; Weick, 1993), benefit from being freed from "organizational slack" (Grabher, 2004, p. 1491), and therefore are described as "hyper-efficient"(Grabher, 2004, p. 1491; Lash & Urry, 2002, p. 124).

Buvik and Rolfsen (2015, p. 1484) state that the transient features of finite time spans influence working in projects. Project teams comprise cross-functional team members with complementary skills targeted to solve complex tasks. Additionally, the team increases its performance through close collaboration with the diverse departments within the organization (Buvik & Rolfsen, 2015, p. 1484). Brown and Eisenhardt (1995, p. 362) state that the processing of different tasks simultaneously represents one advantage of cross-functional teams. Edmondson and Harvey (2018, p. 347) are convinced that cross-boundary teaming increases the output of innovative ideas.

Our case studies showed that the complexity-mastering methods can and should be posited as highly innovative. The temporary organizational form of project teams helps

to identify and to conceptualize these methods successfully. Furthermore, the methods often affect more than one stage along the value chain. Even though they may be operationally implemented in a single department, they usually influence other departments considerably. Therefore, cross-functional perspectives are beneficial for becoming aware of essential interrelationships and effects which need to be incorporated in the implementation phase. Cross-functional team members need to be integrated into the organizational structure after implementing the methods. Some of the case companies adapted their organizational structures and established a dedicated department or function to keep watch over and support the target achievements of the implemented methods. BA, for example, did not implement a dedicated responsibility for the target achievement of the MPS, but retrospectively would have decided differently. Striving for targets of modularity within the overall product portfolio would have been facilitated by introducing a dedicated employee independently of daily work duties.

5.1.7 Stakeholders

The *seventh element – stakeholders* consider further influencing roles inside and outside of the company (see Figure 34).

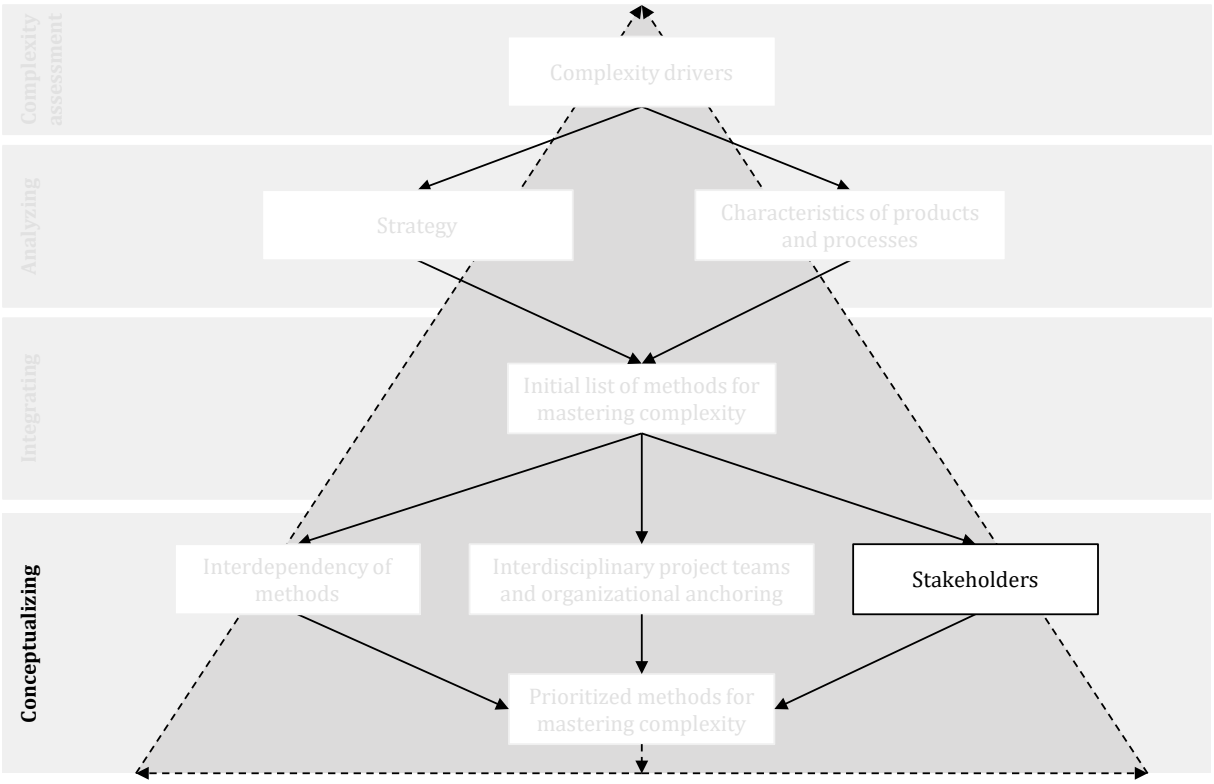


Figure 34: Process model – Element 7: Stakeholders

Some reviewed literature suggests the efficacy of top management stakeholders and user participation during the design and implementation process of methods (Doll, 1985; Kanwal et al., 2017; Lynne Markus, 1981; Young & Jordan, 2008). Various authors emphasize the relevance of top management support in projects (Doll, 1985; Garrity, 1963; Lynne Markus, 1981). Young and Jordan (2008) emphasize top management support as an essential factor for project success. They define top management support as the devotion of a "…senior management project sponsor/champion, the CEO and other senior managers […] to review plans, follow up on results and facilitate management problems" (Young & Jordan, 2008, p. 720).

Zwikael (2008, p. 393) investigated the effects of top management support on project success measures, identifying significant positive relationships for keeping to schedule and cost targets, along with ensuring satisfactory project performance and customer satisfaction.

Young and Jordan (2008, pp. 719–720) maintained that top management support is often necessary but emphasized the necessity of user involvement to achieve success in projects.

Successful implementation of methods also requires user participation. Users are understood in industrial product and process innovations as being involved in the integration of innovations into a final product or a process (von Hippel, 1988). Economic motives suggest an interaction between developers and potential users of innovations (Gales & Mansour-Cole, 1995, p. 79). User involvement helps to convince these users, to tailor the methods to the needs, and to overcome resistance, and to awaken a sense of commitment in the user (Lynne Markus, 1981, pp. 12–13). Therefore, all of the case companies included the future users of the method in the process of identifying and conceptualizing the complexity-mastering methods.

However, participation is not a universal solution for acceptance by all companies. Top management attention can be beneficial in creating acceptance of newly implemented methods (Lynne Markus, 1981, p. 13). Young and Jordan (2008) state that combining top management support and user involvement assists in achieving success in the implementation of projects. Transparency of the top management in resolving issues and conflicts has a positive impact on user involvement (Young & Jordan, 2008, pp. 719–720). Top management support was actively involved at AC, PC, and FC, which supported the acceptance of the methods within the organization.

The various stakeholders along the value chain incorporate valuable perspectives in the process of identifying and conceptualizing methods for mastering complexity. Hierarchically well-positioned stakeholders and experts from individual stages along the value chain add insights to this process. With an integrated view on the entire organization, these stakeholders contribute to interdisciplinary optimization. Furthermore, top-management support helps to efficiently roll out methods within the organization.

On the other hand, experts in the value chain contribute valuable in-depth knowledge to identify the challenges and benefits of methods. Additionally, their perspective adds support in evaluating the feasibility and suitability of the methods. Especially cross-functional teams help to identify valuable solutions impacting the entire value chain. Early involvement of stakeholders along the value chain permits the identification of interrelationships between stages and their linked methods. This facilitates an implementation of methods jointly and increases the optimization potential for the organization.

5.1.8 Prioritized methods for mastering complexity

In this subchapter the last element of the process model is described (see Figure 35). Here all information and insights from the elements 1-7 are collected and analyzed. If enough information is available, a prioritized list of methods for mastering complexity is derived. Otherwise the iterative character of the process model suggests analyzing other elements again in order to gain full clarity and transparency regarding the suitable methods for mastering the complexity of the organization.

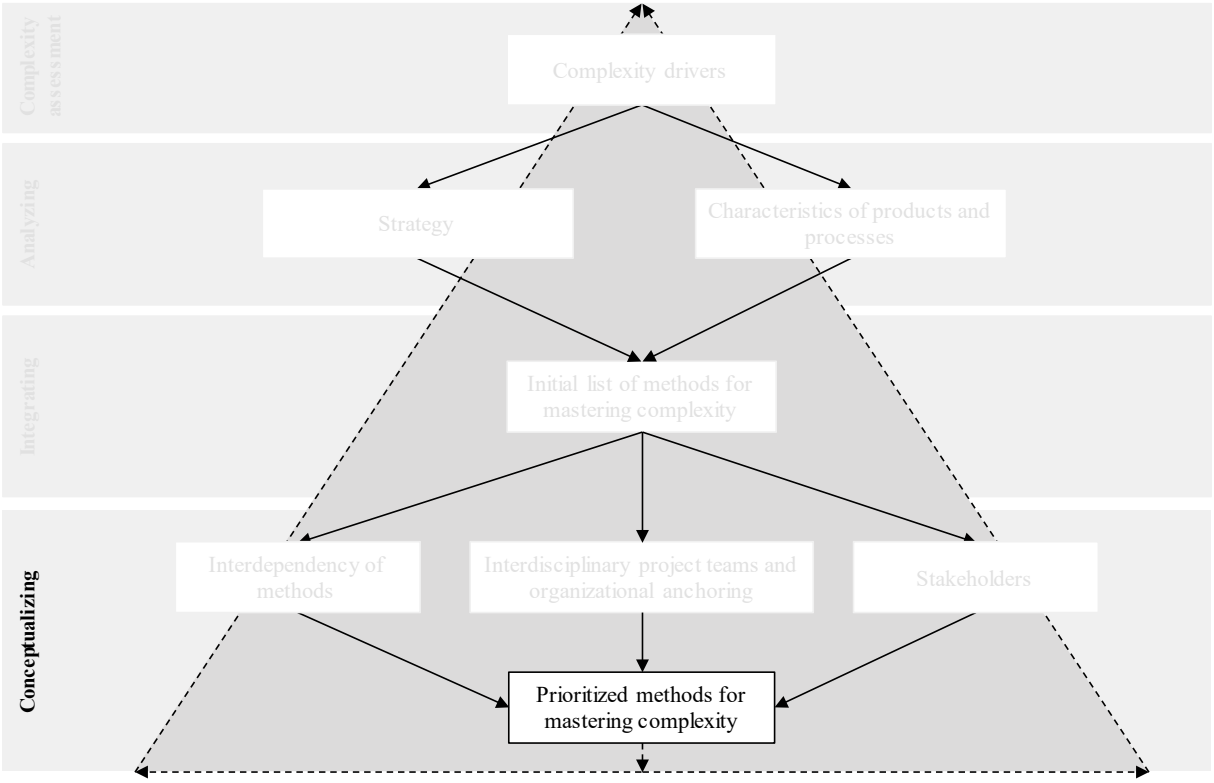


Figure 35: Process model – Element 8: Prioritized methods for mastering complexity

5.2 Exemplary application of the process model for mastering complexity

Due to time restrictions, it was not possible to test the entire process model in a real application. Nevertheless, the research author was able to accompany a manufacturing company in the medical technology industry (Medical Technology Company, MTC) along the first three steps of the process model (see Figure 36). The following subchapter describes and elaborates on:

- First, the complexity drivers, their impacts on the value chain
- Second, the elements of MTC‘s strategy, as well as the products and the processes;
- Third, the list of methods for mastering complexity identified by MTC and the methods derived based on this dissertation’s relationship matrix[34];

[34] For detailed description refer to chapter 5.1.4.

- Fourth, the outlook on the next steps for conceptualizing these methods.

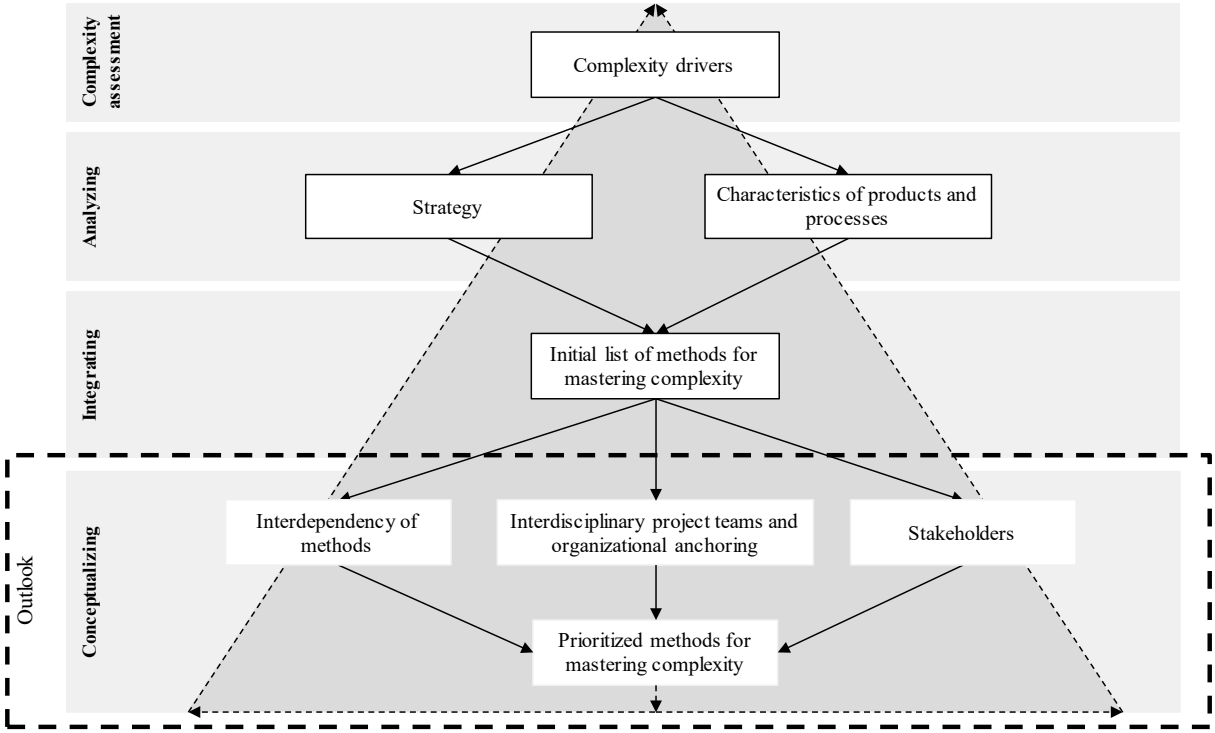


Figure 36: Process model applied at MTC

Element 1 – Complexity drivers

The analysis of the causes of complexity resulted in the identification of seven main complexity drivers. Especially the *variety* and *the individuality of the customer demand* combined with the *total number of the customers* resulted in a high complexity. Because of individual customer demand, the company created a high *variety in the product portfolio*, i.e., on the packaging side. In the medical technology industry, especially in the field of implants, the *regulatory requirements* lead to extensive documentation efforts. As a result, these efforts lead to an increase of complexity in all processes. Additionally the complexity of the company is driven by the *product structure* and the *manufacturing and supply chain processes*.

List of complexity drivers

- Variety of customer demand
- Individuality of customer demand
- Number of customers

- Variety of products
- Regulatory requirements
- Product structure
- Variety of production and supply chain processes

Element 2 – Strategy

As part of the strategy the company aims at creating high quality and sustainable innovation. New developments are scientifically investigated until they fulfill the standards of quality, safety, and therapeutic effects. The company plans to exploit new, international markets. Currently, new customer orders and individual requests are consistently fulfilled, without estimating the added costs along the processes.

Element 3 – Characteristics of products, production, and supply chain

To identify suitable methods for mastering the complexity drivers, the technical characteristics of the products and processes need to be investigated. Based on the ingredients of the products, the complexity of the product portfolio may increase, since the sources of the raw materials, as well as the products, are not registered in all markets. Hence, the variant creation point starts from sourcing the raw materials. As a result, the production lines have to be separated in order not to mix up the resources or products. These circumstances have led to a total number of 294 product variants – for one product series alone.

The order process type is mainly MTO driven, due to the perishable final products and semi-finished products. Hence, methods for increasing the speed and flexibility of the production processes are beneficial in fulfilling the business needs of fast delivery of individualized products. The complexity along the value chain lies mainly in the departments of procurement, pre-series production, warehousing, and confectioning of the final products.

Element 4 – Initial list of methods for mastering complexity

Based on this information, the company derived an initial list of five methods:

- Transparency of complexity development
- Transparency of complexity cost
- Decision support based on complexity costs for new product variants

- Postponement
- Standardization of packaging

The company identified two methods for generating transparency in the complexity development and the cost impacts of complexity within the organization. Based on this transparency, a third method was identified to support the decision-making process regarding new product variants. Therefore, customer orders and individual requests were to be evaluated regarding their contributions to sales and added complexity.

This method provides a contrast to the current approach of generally accepting all customer orders and requests. Therefore, the company needs to investigate how to combine the method with the current strategy.

Additionally, MTC identified *postponement,* and *standardization of packaging* as methods to handle their complexity drivers. *Postponement allows shifting the customer penetration point to a later stage.* This method is linked to the complexity driver *variety of production and supply chain processes*. *Standardization of packaging* allows for reducing the number of packaging variants on the customer side with respect to IFU, languages, design of package. It is linked to the complexity driver *variety of products.*

Additional methods derive from this dissertation's relationship matrix. Therefore, the complexity drivers of MTC identified in the first element of the process model were selected as shown in Table 39. The identified relationships between complexity drivers and methods for mastering complexity from the literature, quantitative study and cases suggest methods to be taken into consideration for MTC.

Table 39: Thesis' relationship matrix applied to MTC

		Methods									
		Product portfolio management	*Requirements engineering*	*Global management of modular product platforms*	*Modularity of products*	*Modularity of production processes*	*Technology Super Market (TSM)*	*HCM*	*Standardization of assemblies*	*Preferred series*	*Reuse of parts search*
Origin	***Complexity drivers***										
Factors identified from quantitative study	*Production and value chain complexity*		•	•	•/+	+		•			
	Product and market dynamics	•/+	•	•/+	•	•	•	•			
	Product and market variety	•	•	•	•	•	•	•	•	•	•
	Legal and political factors		+		-	•	•				
Complexity drivers identified from cases	*Product structure*		-				•	•		•	
	Number of products/parts		•		•		•	•	•	•	•
	Variety of production & SC processes		•				•	•	•	•	•

• Relationship identified from the literature & cases

+/- Relationship identified in the quantitative study

Therefore, in this step we added the following methods to the list of suitable methods to address the complexity drivers.

- Product portfolio management
- Requirements engineering
- Global management of modular product platforms
- Modularity of products
- Modularity of production processes
- Technology Super Market
- Standardization of production and assembly processes

- Holistic Complexity Management (HCM)
- Standardization of assemblies
- Preferred series
- Reuse of parts search

As shown in Figure 36, this dissertation's process model was not fully applied at MTC. Especially *phase 4, conceptualization of methods*, is a highly iterative step in the process and takes time within an organization. This step assures that the methods fit to socio-technical system of the company. Therefore, now an outlook of the steps to derive a final selection of methods to master the complexity at MTC is described.

Outlook: Phase 4 – conceptualization of methods

As a next step, the company conceptualizes these methods in phase 4 of the process model. The *interdependency of the methods* is analyzed to align the approaches within the organization. *Interdisciplinary project teams* – participating departments depend on the method – are set up, and the *organizational anchoring* of the team defined. On the one hand, the interdisciplinary project teams generate valuable information to evaluate the feasibility of the methods. On the other hand, the suitability of the methods for mastering the individual complexity of the company can be evaluated.

Additionally, further valuable *stakeholders*, outside of the project team, are defined. These stakeholders are selectively involved in the project for workshops, interviews, and discussions. As a result of the conceptualizing step, the methods for mastering complexity are evaluated regarding their feasibility, and time frames are constructed. These methods are constantly involved in a cycle of being challenged and aligned with the characteristics of the company. Furthermore, the cyclic character of the process model permits the evaluation of the results of the projects and their impacts on the organization.

5.3 Conclusion and summary

This chapter was based on the insights of this dissertation from the theory, quantitative study and case study research. Here the suggested process model of this dissertation for identifying and conceptualizing methods for mastering complexity was described. As

an introduction the process model was outlined and the contribution of the theoretical background of the contingency and the STS theory was elaborated on. In subchapter 5.1 the eight elements of the process model were described. Subchapter 5.2 applied the first three phases the model to MTC and derived a first list of methods for mastering complexity. The outlook of *phase 4* for conceptualizing these methods in order to prioritize was then described.

6 Summary and outlook

This chapter first summarizes the results of the dissertation and critically reflects on possible outcomes in subchapter 6.1. Subchapter 6.2 elaborates on the scientific and managerial implications; in subchapter 6.3 the limitations and future research are described.

6.1 Summary of results and critical reflection

Researchers and practitioners are demanding more insights into the processes of manufacturing companies to identify and conceptualize methods for mastering complexity. The literature reviewed in this present study indicates that organizations definitely need to understand their complexity drivers to manage complexity. Several influencing factors were analyzed here to outline and develop a process model to assist managers in identifying and conceptualizing methods for mastering complexity. The main research question was formulated in this study as follows:

MRQ: *How can manufacturing companies be supported in mastering their complexity?*

To answer this research question, a mixed methods approach was applied. Five SRQs served to answer the MRQ. A summary of the findings used to answer the SRQs now follows.

SRQ 1: *What are complexity drivers along the value chain in the manufacturing industry?*

An initial literature review enabled the author to gain an overview of complexity drivers. These insights were tested and refined with regard to the manufacturing industry, based on interviews, discussions, and workshops with 18 executives from international manufacturing companies, in an iterative process. As a result, the research team derived a list of 19 complexity drivers for manufacturing companies. The first SRQ aimed at analyzing the relevance of these complexity drivers along the value chain in the manufacturing industry. Based on the data from 130 companies, the research team identified the relevance of the complexity drivers. The results showed that the three most

relevant complexity drivers are *variety of products, variety of customer requirements* and *number of customers*.

SRQ 2: *What is the underlying structure of the complexity drivers?*

Addressing the need for reducing the set of complexity drivers in the manufacturing industry (Sousa & Voss, 2008, p. 704), an explorative factor analysis (EFA) was conducted. The EFA was able to identify strong correlations, which resulted in six underlying factors. Based on a qualitative understanding, the factors were interpreted as p*roduction and value chain complexity, product and market dynamics, product and market variety, supply uncertainty, legal and political forces,* and c*orporate structure and culture*.

SRQ 3: *What methods exist for mastering complexity along the value chain in the manufacturing industry?*

As a result of a literature review methods for mastering complexity in the manufacturing industry were identified. Applying a funnel model led to the identification of pertinent methods for mastering complexity. The final five methods were evaluated in the quantitative study, with respect to the implementation degree in 130 manufacturing companies. The result showed that the implementation degree of the methods is rather mediocre.

SRQ 4: *What are the influencing factors for identifying and conceptualizing methods for mastering complexity in the manufacturing industry?*

Since the results from SRQ 3 did not indicate significant differences between the methods, SRQ 4.1 analyzed the impact of complexity drivers on the methods for mastering complexity. Furthermore, in SRQ 4.2, additional influencing factors for identifying and conceptualizing these methods were also analyzed.

> ***SRQ 4.1:*** *What is the relationship between methods for mastering complexity and complexity drivers in the manufacturing industry?*
>
> Based on quantitative data from 130 manufacturing companies, a correlation analysis between the 19 complexity drivers and the five methods for mastering complexity was conducted. The result of the analysis showed low to medium, but significant correlations, which indicated that additional factors influence the choices made by manufacturing companies. In addition, in Chapter 4, the relationship between complexity drivers and methods for mastering complexity was analyzed based on case study research. Similar relationships between

complexity drivers and these methods were identified in the literature reviewed, case studies and the quantitative study.

SRQ 4.2: *How do other factors influence manufacturing companies in identifying and conceptualizing methods for mastering complexity?*

Based on case study research the author conducted explorative research regarding further influencing factors for identifying and conceptualizing methods for mastering complexity at five manufacturing companies. The author identified six common influencing factors in the five case companies: *Complexity drivers, stakeholders, strategy, interdisciplinary project teams, dependency of methods*, and *characteristics of products, production, and supply chain*. However, the individual manifestation of the elements in the case companies for identifying and conceptualizing methods for mastering complexity differs.

SRQ 5: *How can a process model for identifying and conceptualizing methods for mastering complexity be designed?*

The literature review indicated that research regarding support models for mastering complexity is scarce. Thus, it is unclear how manufacturing companies can be supported in identifying and conceptualizing methods for mastering complexity. Based on the results from Chapter 4 the author derived a process model to support managers. Six common influencing factors were integrated as elements into the iterative process model, consisting of four stages:

- The first step aims at assessing complexity based on the complexity drivers of the company. Based on an idealized relationship matrix, and with the help of insights from the literature, quantitative study, and case study research, a first set of methods can be identified;
- Second, an internal analysis also serves as a basis to;
- Third, a list of methods for mastering the complexity drivers is identified;
- Fourth, the methods are conceptualized. The fourth step also includes the re-evaluation of the methods with respect to the characteristics of the company, adding a cyclical character to the process model.

6.2 Implications

6.2.1 Scientific implications

This present study will hopefully contribute to the body of knowledge in the field of complexity management. It relies and expands upon the literature in this field. The relevance of complexity drivers and the implementation degree of methods for mastering complexity were tested in a large-scale quantitative study in the manufacturing industry. The findings in the literature were compared extensively with the quantitative results. Based on this data, the research team conducted an explorative factor analysis, resulting in a deeper understanding of the underlying structures of the complexity drivers. Six clusters of complexity drivers were derived, simplifying their understanding.

Furthermore, studies included in this dissertation have contributed to the understanding of contingencies in the field of mastering complexity. A correlation analysis of the methods for mastering complexity and the complexity drivers demonstrated mediocre relationships. The case study research also revealed six common influencing factors for identifying and conceptualizing methods for mastering complexity in an explorative manner. These factors from the case companies were integrated into a process model.

In addition to the contingency theory, our research made use of the socio-technical systems theory. The principles of the socio-technical systems theory are partly supported by the derived process model, which can support manufacturing companies in managing the socio-technical challenges of identifying and conceptualizing methods for mastering complexity.

6.2.2 Managerial implications

Managerial problems in manufacturing companies motivated the author to carry out the research detailed in this dissertation. Especially emphasized were the struggles of managers to identify and conceptualize suitable methods to deal with the individual complexity and characteristics of their companies. The multifaceted characteristics of complexity management were identified as the main reason for these complexity phenomena. The relevance of complexity drivers and the implementation degree of methods for mastering complexity in the manufacturing industry were analyzed. An exploratory factor analysis of the complexity drivers resulted in a dimension reduction, allowing managers to identify the complexity of their organizations more efficiently.

Based on insights from five cases in the manufacturing industry a process model was derived to support managers in identifying and conceptualizing methods for mastering complexity. This process model, consisting of six elements, can be valuable for managers in understanding the individual complexity and the needs of their companies.

6.3 Limitations and future research

This research study has several limitations which may provide a starting point for future research:

- Due to time constraints, the studies carried out for this dissertation did not test the long-term efficacy of the process model in supporting the identification and conceptualization of methods for mastering complexity. Even though the usefulness of the process model was evaluated based on interviews with executives, and a partial application in a medical technology company, it remains unclear if applying the process model will provide support in mastering complexity in the long-term. Therefore, a longitudinal study regarding the optimization of complexity should be conducted.
- Case study research was applied for developing the process model. While the correlation between complexity drivers and the methods for mastering complexity were analyzed, the elements of the process model were not confirmed through a quantitative analysis. The case studies did, however, provide in-depth and exploratory insights into influencing factors for identifying and conceptualizing methods for mastering complexity, which resulted in a process model containing six elements. Further quantitative research should be conducted to confirm these elements and their order in the process.
- This thesis did not include an operationalization approach for the strategy element in the process model. Further research could investigate on existing frameworks to evaluate on a company's strategy and link it with the complexity drivers and suitable methods.
- The results of the dissertation are based on quantitative research using surveys, along with case study research. Hence, the quality of the data is dependent on the participants of the survey and the informants of the case studies. The author applied

measures to mitigate these risks. In the case studies, the multiple informants were chosen with care, to reduce the risk of single response bias. The quantitative data was tested through interviews with some of the participants. To confirm the results of the explorative factor analysis, the dataset either needs to be split up or a second dataset should be obtained, to carry out a confirmatory factor analysis. Due to the small number of responses, and time constraints, these measures were not applied in this study. Future research should be conducted to verify the findings.

- This dissertation focused on methods of mastering complexity. Further research could investigate methods of measuring and controlling complexity, thus complementing and benefiting the process model suggested in this study.
- Since this dissertation applied the contingency theory and the socio-technical systems theory, further research could investigate the topic from a different perspective, for example from a resource-based perspective.

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APPENDIX A: LITERATURE REVIEW

The table below contains the keywords and the Boolean operators used to construct the final search string regarding the topic *Methods for mastering complexity*.

Key words	Boolean operator
("complexity management"	
"mastering complexity")	OR
	AND
(approach	
method	OR
concept)	OR
	AND
(manufacturing	
production	OR
market	OR
customer	OR
requirements	OR
product structure)	OR

The table below presents the journals, databases, and other relevant publications of the structured literature review regarding the topic *Methods for mastering complexity*.

	Databases				
Journals	**Emerald**	**Science direct**	**Taylor & Francis**	**Wiley**	**Others**
Production and Operations Management				•	
European Journal of Operational Research (EJOR)		•			
IIE Transactions			•		
Manufacturing & Service Operations Management (M&SOM)					•
Journal of Operations Management		•			
International Journal of Production Economics		•			
International Journal of Production Research			•		
Decision Sciences				•	
International Journal of Physical Distribution & I	•				
Journal of Supply Chain Management				•	
Journal of Business Logistics				•	
International Journal of Operations & Productior	•				
Flexible Services and Manufacturing Journal (FSM)					•
Journal of Purchasing & Supply Management		•			
Computers and Industrial Engineering		•			
Supply Chain Management: An International Jou	•				
Supply Chain Forum: An International Journal			•		
Title, Abstract, Keywords (TAK)	11	7	0	3	10
Relaxed (all fields)	11	394	144	231	40
Relevant after title and abstract	6	15	10	12	1
Relevant after reading	1	7	0	0	0
Relevant publications	8				

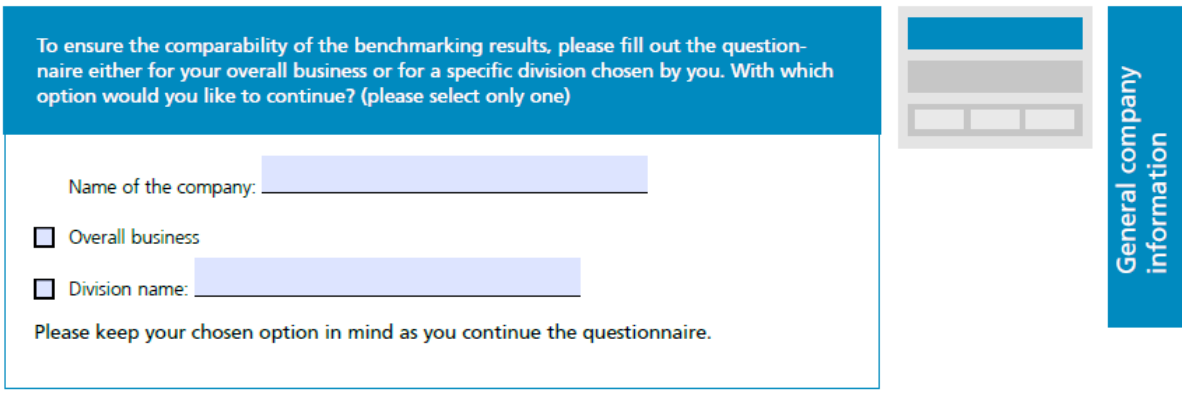
The table below contains the keywords and the Boolean operators used to construct the final search string regarding the topic *Influencing factors for identifying and conceptualizing methods for mastering complexity*.

Key words	Boolean operator		Key words	Boolean operator
("complexity management"			(element*	
"mastering complexity"	OR		factor*	OR
Komplexitätsmanagement	OR		indicator*	OR
Komplexitätsbeherrschung)	OR	AND	source*	OR
			parameter*	OR
	AND		variable*	OR
(approach			symptom*	OR
model	OR		phenomenon	OR
method*	OR		dimension*	OR
concept	OR		force	OR
procedure	OR		property	OR
framework	OR		Faktor*	OR
Ansatz	OR		Indikator*	OR
Methode	OR		Element*)	OR
Konzept)	OR			
	AND			
Manufacturing				
Produktion	OR			
Fertigung	OR			
Production	OR			

The table below lists the journals, databases, and other relevant publications of the structured literature review regarding the topic *Influencing factors for identifying and conceptualizing methods for mastering complexity*.

	Databases				
Journals	**Emerald**	**Science direct**	**Taylor & Francis**	**Wiley**	**Others**
Production and Operations Management				•	
European Journal of Operational Research (EJOR)		•			
IIE Transactions			•		
Manufacturing & Service Operations Management (M&SOM)					•
Journal of Operations Management		•			
International Journal of Production Economics		•			
International Journal of Production Research			•		
Decision Sciences				•	
International Journal of Physical Distribution & Logistics Manag	•				
Journal of Supply Chain Management				•	
Journal of Business Logistics				•	
International Journal of Operations & Production Management	•				
Flexible Services and Manufacturing Journal (FSM)					•
Journal of Purchasing & Supply Management		•			
Computers and Industrial Engineering		•			
Supply Chain Management: An International Journal	•				
Supply Chain Forum: An International Journal			•		
Title, Abstract, Keywords (TAK)	8	8	0	0	0
Relaxed (all fields)	133	382	82	108	7
Relevant after title and abstract	1	3	3	0	0
Partly relevant after reading	1	2	1	0	0
Relevant publications after forward backward search	9				

APPENDIX B: STUDY QUESTIONNAIRE



To ensure the comparability of the benchmarking results, please fill out the questionnaire either for your overall business or for a specific division chosen by you. With which option would you like to continue? (please select only one)

General company information

Name of the company: _____

☐ Overall business

☐ Division name: _____

Please keep your chosen option in mind as you continue the questionnaire.

01. Which industry does your company (primarily) belong to?

☐ Mechanical/plant engineering	☐ Medical technology
☐ Consumer goods industry	☐ Electronics industry
☐ Aerospace engineering	☐ Optics and precision engineering
☐ Automotive industry	☐ Chemical industry
☐ Pharmaceutical industry	☐ Others: _____

02. Please fill in the key performance indicators for the last financial year.

Revenue (million €)	☐ < 100	☐ 100-500	☐ 500-1.000	☐ 1.000-5.000	☐ > 5.000
Return on sales	☐ < 5 %	☐ 5-10 %	☐ 10-15 %	☐ 15-20 %	☐ > 20 %
Share of R&D expenses regarding the total revenue	☐ < 5 %	☐ 5-10 %	☐ 10-15 %	☐ 15-20 %	☐ > 20 %
Employees total (FTE)	☐ < 50	☐ 50-250	☐ 250-1.000	☐ 1.000-10.000	☐ > 10.000

03. Please determine the average development of the following key performance indicators over the last three years.

	< -10 %	-10 % to -5 %	-5 % to +5 %	+5 % to +10 %	> +10 %
Market share	☐	☐	☐	☐	☐
EBIT (Earnings before interest and taxes)	☐	☐	☐	☐	☐
ROI (Return on investment)	☐	☐	☐	☐	☐

General company information

04. What kind of products are mainly produced in your company (concerning the number of parts)?

- ☐ Individual parts/components (1-10 parts)
- ☐ Assembly groups (ca. 100 parts)
- ☐ Machines (ca. 1.000 parts)
- ☐ Heavy machines/plant engineering
- ☐ Process industry goods

05. Which type of manufacturing is used for the majority of your products?

- ☐ Piece/small-batch production (< 20 pieces/month)
- ☐ Batch production (20-1.000 pieces/month)
- ☐ Mass production (> 1.000 pieces/month)
- ☐ Continuous production process (process industry)

06. Which type of order processing is implemented for the majority of your products? (multiple selections possible)

- ☐ Engineer to order
- ☐ Make to order/assemble to order
- ☐ Configure to order
- ☐ Make to stock

The type of order processing describes the degree of customer involvement in processing orders.

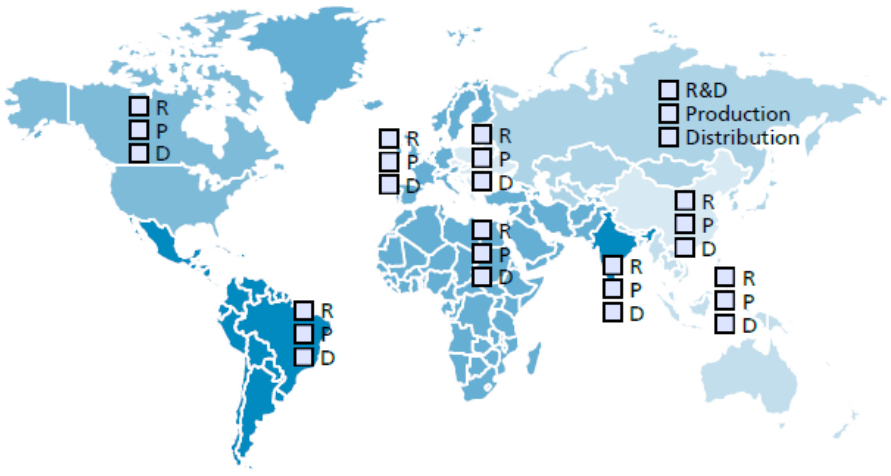
07. The depth of added value of our products is...

very low (e.g. only final assembly/ packaging)	low	medium	high	very high (e.g. own manufacturing and assembly)
☐	☐	☐	☐	☐

08. How many research and development, production and distribution sites do you operate globally?

R&D: _____ Production: _____ Distribution: _____ Total: _____

09. Please mark the sites on the map.



10. How would you rate the influence of the following external complexity drivers on the complexity in your company? Are key performance indicators (KPIs) used to measure the complexity drivers?

	Very low				Very high	KPI
Legal factors	☐	☐	☐	☐	☐	☐
Political conditions	☐	☐	☐	☐	☐	☐
Number of customers and customer groups	☐	☐	☐	☐	☐	☐
Variety of customer requirements	☐	☐	☐	☐	☐	☐
Volatility of customer demand	☐	☐	☐	☐	☐	☐
Competitive dynamics	☐	☐	☐	☐	☐	☐
Number of suppliers	☐	☐	☐	☐	☐	☐
Uncertainty regarding delivery dates	☐	☐	☐	☐	☐	☐
Uncertainty regarding delivery quality	☐	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐	☐

Complexity drivers are factors that increase the complexity in the company. There are external and internal complexity drivers.

11. How would you rate the influence of the following internal complexity drivers on the complexity in your company? Are key performance indicators (KPIs) used to measure the complexity drivers?

	Very low				Very high	KPI
Product variety	☐	☐	☐	☐	☐	☐
(Product) Program dynamics	☐	☐	☐	☐	☐	☐
Product structure	☐	☐	☐	☐	☐	☐
Product technology dynamics	☐	☐	☐	☐	☐	☐
Crosslinking degree of company processes	☐	☐	☐	☐	☐	☐
Number of value-added steps	☐	☐	☐	☐	☐	☐
Production technology dynamics	☐	☐	☐	☐	☐	☐
Number of distribution levels	☐	☐	☐	☐	☐	☐
Organizational structure	☐	☐	☐	☐	☐	☐
Corporate culture	☐	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐	☐

Handling complexity in your company

Complexity management comprises the design, controlling and development of the variety of the performance spectrum (products, processes and resources) of the company. By reinforcing or mitigating the complexity, this variety can be adjusted throughout all value-added steps so that a maximum customer benefit can be generated whilst at the same time a high level of profitability is ensured.

12. For how long has your company been working on the topic complexity management?

For (approx.) _____ year(s)

☐ No implementation of methods of complexity management so far

13. Please state to which degree complexity management is part of your strategy.

low degree ☐ ☐ ☐ ☐ ☐ high degree

14. How is the responsibility for complexity management implemented?

☐ Permanent implementation

☐ Temporary project teams

☐ No implementation

If a permanent implementation has been chosen, who is mainly responsible?

☐ Development department

☐ Production

☐ Product management

☐ Special department within the company

☐ Permanent cross-functional teams

☐ Others: _____

15. In which fields have complexity management projects already been carried out? (multiple selections possible)

☐ End-to-end value chain

☐ Product portfolio

☐ Organization

☐ Supply chain network

☐ Production

☐ Sales

☐ Service/after sales

☐ Procurement

☐ Development

☐ No projects so far

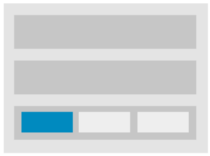
☐ Others: _____

16. Which of the following targets are highly prioritized concerning your complexity management? To what extent have you been able to achieve these targets?

	Target of high priority does not apply ... fully applies					Target has been achieved does not apply ... fully applies				
Reduction of product complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Broader product program	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
More innovative products	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shorter time-to-market	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reduction of production costs	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reduction of process variety	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Production agility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Order quantity flexibility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Delivery time optimization	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Service optimization (e.g. after-sales/support)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
_____	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
_____	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

17. To which extent do the following statements on complexity controlling apply?

	does not apply ... fully applies				
"Compliance with complexity guidelines is controlled globally throughout the network."	☐	☐	☐	☐	☐
"The performance of the company-wide complexity management is measured on a regular basis."	☐	☐	☐	☐	☐
"The performance of complexity management can be quantified."	☐	☐	☐	☐	☐



Market complexity

One major task of complexity management is the transfer of external requirements, such as regional customer requirements or regulatory requirements, into the product portfolio. Product management and sales department play a pivotal role in managing this external market complexity. An efficient internal realization of the externally induced complexity is possible through an integrated, holistic view.

18. Who has the decision-making responsibility concerning the following categories?

	decentralized				centralized
Marketing	☐	☐	☐	☐	☐
Sales	☐	☐	☐	☐	☐
Pricing	☐	☐	☐	☐	☐
Product management	☐	☐	☐	☐	☐

Decentralized responsibility describes a high self-responsibility of the local sites.

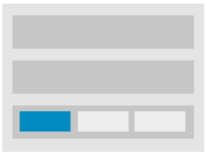
Centralized responsibility means that major decisions are made by a central function. They are mandatory for all sites in the global network.

19. How have the following key performance indicators developed over the last three years? (if no data is available, please make an estimation)

	< -20 %		-5 % to +5 %		> +20 %
Number of offered product variants	☐	☐	☐	☐	☐
Revenue per offered product variant	☐	☐	☐	☐	☐
Profit per offered product variant	☐	☐	☐	☐	☐

20. To which extent do the following statements on variant development apply?

	does not apply				fully applies
"The introduction of new variants follows a clearly defined process."	☐	☐	☐	☐	☐
"The sales department supports product management with market analyses and order quantity forecasts on a regular basis."	☐	☐	☐	☐	☐
"The sales department is aware of the additional efforts throughout the value-added areas that are caused by a large number of variants."	☐	☐	☐	☐	☐
"When introducing a new product variant, life cycle costs are considered in decision-making."	☐	☐	☐	☐	☐



Market complexity

21. To which extent do the following statements on the sales process apply?

	does not apply				fully applies
"All employees in the sales department are able to explain the differences between our product variants to the customers."	☐	☐	☐	☐	☐
"We motivate our sales employees to preferably offer standard variants to the customers."	☐	☐	☐	☐	☐
"The sales process is supported by product configurators."	☐	☐	☐	☐	☐
"The sales employees are able to differentiate between standard and special variants."	☐	☐	☐	☐	☐
"We are able to enforce minimum order quantities for special variants."	☐	☐	☐	☐	☐
"We are able to enforce sales prices that take account of the complexity costs."	☐	☐	☐	☐	☐

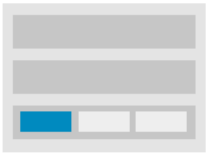
Complexity costs are costs that are caused by the variety and dynamic of the product programs and value-adding processes in the company.

22. To which extent do the following statements on product portfolio management apply?

	does not apply				fully applies
"We were able to increase the portfolio profitability by a complexity cost based pricing."	☐	☐	☐	☐	☐
"The product complexity is made transparent throughout the whole product portfolio (e.g. by using feature trees)."	☐	☐	☐	☐	☐
"Removal of variants from the portfolio follows a clearly defined phase-out process."	☐	☐	☐	☐	☐
"Decisions about the phase-out of product variants are compulsorily made based on clearly defined criteria."	☐	☐	☐	☐	☐
"We use data analytics in order to optimize our product portfolio."	☐	☐	☐	☐	☐

23. To which extent do the following statements on the requirements management apply?

	does not apply				fully applies
"Clear responsibilities have been defined for requirements management."	☐	☐	☐	☐	☐
"A clearly defined structure is used for the aggregation and maintenance of the requirements."	☐	☐	☐	☐	☐
"We have standardized requirements-categories (e.g. financial, process related, product function related)."	☐	☐	☐	☐	☐
"Global and local requirements are explicitly differentiated."	☐	☐	☐	☐	☐
"The requirements management already distinguishes requirement variants."	☐	☐	☐	☐	☐
"The requirements of different markets and market segments are fully transparent and documented."	☐	☐	☐	☐	☐
"We link different requirements with market segments and relevant data (volume etc.)."	☐	☐	☐	☐	☐
"We link requirements with product functions."	☐	☐	☐	☐	☐



Market complexity

Requirements management is the management of product requirements. It comprises the collection, analysis, specification and validation of requirements.

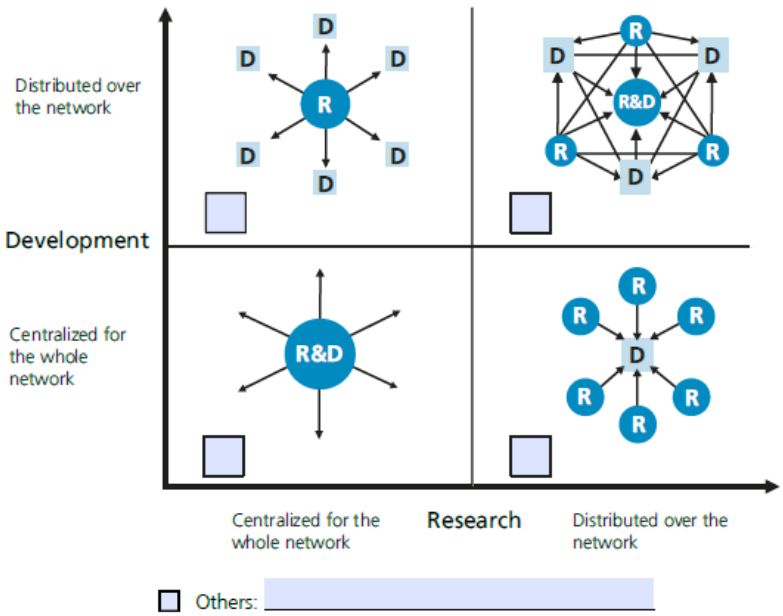
24. Do you use special IT-tools that support requirements management (e.g. IBM Rational DOORS, PTC Integrity etc.)?

☐ Yes ☐ No

→ Which ones: _____

As an answer to the growing external market complexity, strategies for reduction of internal product complexity have been established. They are able to efficiently meet variety and dynamic of product requirements. High potentials can be realized by global modular platforms, which are thus a focus topic of the complexity management.

25. Which image represents your R&D network structure best?



☐ Others: _____

26. Who has the decision-making responsibility concerning the following categories?

	decentralized				centralized
Product design	☐	☐	☐	☐	☐
Modular product platform design	☐	☐	☐	☐	☐
Product technology choice	☐	☐	☐	☐	☐

Modular product platforms describe products and product programs that are made up of modules with standardized interfaces. Different product variants can be realized by combining different module variants.

27. How have the following key performance indicators developed over the last three years? (if no data is available, please make an estimation)

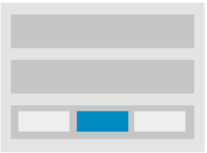
	< -20 %		-5 % to +5 %		> +20 %
Number of item numbers	☐	☐	☐	☐	☐
Number of functions	☐	☐	☐	☐	☐
Number of product technologies	☐	☐	☐	☐	☐

28. For which markets do you develop your products?

☐ Local ☐ Global markets ☐ Local & global markets

If you develop products for local markets, how do you ensure that they stay local? (multiple selections possible)

☐ Technical barriers (e.g. incompatibility with existing infrastructures)
☐ Certifications (e.g. regional incompatibility with regulatory requirements)
☐ Product design (e.g. incompatibility with local user behavior)
☐ Pricing (e.g. regional fees)
☐ Others: _____
☐ None



Product complexity

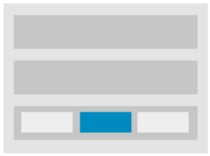
Local products are intended to be sold in a confined geographic region. The products are adjusted to local markets (localization).

29. To which extent do the following statements on the global management of modular product platforms apply?

	does not apply				fully applies
"Our products are based on globally standardized modular product platforms."	☐	☐	☐	☐	☐
"Our modular product platforms aim at providing the product variety that is necessary for meeting the different local requirements."	☐	☐	☐	☐	☐
"Local adaptions are realized within the existing modular product platforms."	☐	☐	☐	☐	☐
"There are clearly defined decision rules determining whether a product variant is realized within or outside an existing modular product platform."	☐	☐	☐	☐	☐
"We have clearly defined which modules may be modified locally."	☐	☐	☐	☐	☐
"The modules are developed across multiple business units in a well coordinated way."	☐	☐	☐	☐	☐

30. To which extent do the following statements on the modularity of your products apply?

	does not apply				fully applies
"For our products, we can make changes in modules without changing other modules."	☐	☐	☐	☐	☐
"For our products, functions can be directly added or deleted by adding or removing modules."	☐	☐	☐	☐	☐
"Our product modules have standardized interfaces."	☐	☐	☐	☐	☐



Product complexity

31. Please answer the following questions on commonality and market share of you modular product platforms.

What is the share of modules that are used across different product lines? _____ % of the modules

What is the share of module variants that are used globally? (in terms of value and with regard to the entire modular product platform) _____ % of the modules

What share of the total market volume can be served with your modular product platforms? (referring to revenue and number of customers) _____ % of the revenue

_____ % of the customers

32. To which extent do the following statements on the IT-support of your product complexity management apply?

	does not apply				fully applies
"We have a globally homogenous IT-landscape."	☐	☐	☐	☐	☐
"We have a transparent overview of all revision levels of product designs in our company."	☐	☐	☐	☐	☐
"KPIs are used to compare the product complexity of our products."	☐	☐	☐	☐	☐
"Compliance with global standards is ensured by rights management in the IT-systems."	☐	☐	☐	☐	☐
"Design guidelines and standards (e.g. for the modular product platforms) are implemented in global IT-systems."	☐	☐	☐	☐	☐
"We use standardized classifications and nomenclature in our ERP-systems."	☐	☐	☐	☐	☐
"We use data analytics in order to optimize our product complexity."	☐	☐	☐	☐	☐

33. Which forms of documentation are used for interfaces and modular product platform standards? (multiple selections possible)

☐ CAD-specifications
☐ Excel
☐ PDM-systems
☐ Module profiles
☐ Shell model
☐ Design rules (e.g. design rule book)
☐ Others: _____
☐ None

How are these standards globally communicated across the company? (multiple selections possible)

☐ E-mails
☐ Trainings
☐ IT-tools
☐ Wikis
☐ Information documents
☐ Others: _____

Product complexity

34. Which view have you chosen for demonstrating the product structure (views on bill of material)? (multiple selections possible)

- ☐ Requirements oriented view
- ☐ Function oriented view
- ☐ Assembly/production oriented view
- ☐ Modular product platform/module oriented view
- ☐ Economic/pricing oriented view
- ☐ Others: _____

Supply chain and production complexity

Market and product complexity relate directly to the supply chain and production complexity which must be able to react flexibly to the complexity of the market and the product. Economies of scale in the procurement and production - particularly regarding global value chains - are one major part of the potentials of a successful complexity management. An integrated view on the entire value chain is required for their realization.

35. Please chose the figure that best describes your production network structure.

☐ World factory



A world product is produced at a single site; Markets are served by export.

☐ Hub and spoke



The main share of manufacturing is conducted at a single hub. To meet the market specifications, products are adapted at local sites.

☐ Local for local



Markets are served by local manufacturing sites with products tailored to the specific market requirements.

☐ Sequential or convergent



The production process is organized as a sequential or convergent chain with production steps conducted at different sites.

☐ Web structure



All sites have almost the full set of competence. Orders are balanced in the network to achieve a high degree of capacity utilization.

36. Who has the decision-making responsibility concerning the following categories?

	decentralized				centralized
Procurement	☐	☐	☐	☐	☐
Make-or-buy decisions	☐	☐	☐	☐	☐
Selection of the production technology	☐	☐	☐	☐	☐
Production capacities	☐	☐	☐	☐	☐
Quality level	☐	☐	☐	☐	☐
Process management	☐	☐	☐	☐	☐

37. How has the complexity of the procurement and the production network changed over the last three years? (if no data is available, please make an estimation)

	< -20 %		-5 % to +5 %		> +20 %
Number of suppliers	☐	☐	☐	☐	☐
Number of bought-in parts	☐	☐	☐	☐	☐
Number of production technologies with the same function (e.g. different welding technologies)	☐	☐	☐	☐	☐
Number of process variants for the same production process (alternative process steps in the entire process)	☐	☐	☐	☐	☐

38. Which procurement sources do you use?

☐ Local sourcing ☐ Global sourcing ☐ Local & Global sourcing

If you source locally, please rate the following statements.

	does not apply				fully applies
"We are able to integrate local suppliers into our supply chain without increasing the internal variety."	☐	☐	☐	☐	☐
"We are able to significantly reduce costs by deploying local suppliers."	☐	☐	☐	☐	☐

39. Which procurement strategies are applied in your company? (multiple selections possible)

- ☐ Single sourcing
- ☐ Dual sourcing
- ☐ Multiple sourcing
- ☐ Modular sourcing
- ☐ Others: _____



Modular sourcing is a procurement strategy in which purchased modules/subsystems have a relatively large range of functions. The aim is to reduce the number of suppliers and the module variety.

40. Do you use modular production toolkits?

☐ Yes ☐ No, but planned ☐ No, not planned

If yes, which elements are standardized within the production

	does not apply				fully applies
Process orders	☐	☐	☐	☐	☐
Assembly orders	☐	☐	☐	☐	☐
Operating supplies	☐	☐	☐	☐	☐
Production technologies	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐
Others: _____	☐	☐	☐	☐	☐

Modular production toolkits allow for the application of the same production elements across different factories, products and derivatives by using standardized production elements.

41. To which extent do the following statements on the application of modular production toolkits apply?

	does not apply				fully applies
"We were able to significantly reduce the planning effort for new sites and production lines by using modular production toolkits."	☐	☐	☐	☐	☐
"Our production exploits the potentials of modular production toolkits systematically."	☐	☐	☐	☐	☐
"Production requirements are taken into account while designing modular product platforms."	☐	☐	☐	☐	☐
"Through modularization of production, the ramp-up phase for new products could be reduced significantly."	☐	☐	☐	☐	☐
"Through the use of modular production toolkits, production costs could be reduced significantly."	☐	☐	☐	☐	☐
"Products based on the same modular product platform can be manufactured on the same production lines."	☐	☐	☐	☐	☐

42. How do you implement the production of a new product at multiple sites chronologically (dual-/multi manufacturing)?

- ☐ Parallel
- ☐ As required
- ☐ Sequentially
- ☐ No application

43. To which extent do the following statements on the production processes apply?

	does not apply				fully applies
"Our production processes are composed of process modules (or self-contained processing units)."	☐	☐	☐	☐	☐
"Sub-processes can be added to or removed from our production processes without changing other sub-processes."	☐	☐	☐	☐	☐
"Our production processes are designed to be rapidly disassembled and reconfigured."	☐	☐	☐	☐	☐
"Only minor equipment modifications are required to produce different products."	☐	☐	☐	☐	☐

44. To which extent do the following statements on the monitoring of process complexity apply?

	does not apply				fully applies
"The complexity of our production processes is monitored continuously."	☐	☐	☐	☐	☐
"Costs of production process complexity are transparent and quantifiable."	☐	☐	☐	☐	☐
"KPIs are used to compare the production complexity at different sites in our production network."	☐	☐	☐	☐	☐
"We use guidelines for dealing with process complexity."	☐	☐	☐	☐	☐
"Complexity is taken into consideration for decisions on production allocation."	☐	☐	☐	☐	☐
"Industrie 4.0 methods are applied to gain control over the complexity in production processes."	☐	☐	☐	☐	☐

Industrie 4.0 is characterized by the real-time, intelligent, horizontal and vertical networking of people, machines, objects and ICT-systems and allows for a dynamic management of complex systems.

Success factors

45. Please tick off the – from your point of view – most important success factors of complexity management in your company/business unit. (max. 3)

- ☐ Top management support
- ☐ Product modularization
- ☐ Production modularization
- ☐ Organizational implementation
- ☐ Interdisciplinary responsibilities
- ☐ IT-tools/virtualization
- ☐ Complexity costs accounting
- ☐ Communication
- ☐ Requirements management
- ☐ Employee trainings
- ☐ Others: _____
- ☐ None

46. From your point of view, please name the companies which operate successfully with global complexity management.

1. _____
2. _____
3. _____

47. What is your personal success story in complexity management? Are there experiences you would like to share?

Feedback

Your feedback for us...

CURRICULUM VITAE

Personal Data

Name	Dominik Kohr
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Education

2014 – 2020	**University of St.Gallen**, St. Gallen, Switzerland
	Doctoral Studies in Business Innovation (Dr. oec. (HSG))
2012 – 2014	**RWTH Aachen University**, Aachen, Germany
	Studies in Business Administration and Engineering (M.Sc.)
2012 – 2013	**Tsinghua University**, Beijing, China
	Studies in Management Science and Engineering (M.Sc.)
2007 - 2012	**RWTH Aachen University**, Aachen, Germany
	Studies in Management Science and Engineering (B.Sc.)
2000 – 2007	**Gymnasium Obersberg**, Bad Hersfeld, Germany
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Professional Experience

Since 2019	**Hilti AG**, Schaan, Liechtenstein
	Technical Project Manager
2014 – 2018	**University of St.Gallen**, St. Gallen, Switzerland
	Research Associate at the Institute of Technology Management (ITEM-HSG), Division of Production Management
2013 – 2014	**BMW AG**, Munich, Germany
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