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Complexity management in variant-rich product development

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Abstract

Complexity is the paradigm of the 21st century and has been discussed in several fields of research. During the last years, increasing complexity in manufacturing companies has been one of the biggest issues in science and practice. Companies in high-technology marketplaces are confronted with technology innovations, dynamic environmental conditions, changing customer requirements, globalization of markets and competitions, as well as market uncertainty, inducing an increasing amount of complexity. Manufacturing companies cannot escape these trends. In today's highly competitive environment, it is fundamental for company's success to develop and launch new products quickly and with customer's individual settings to the market. The companies cope with these trends by developing new product variants, which lead to an increased complexity in the company and in product development. Complexity is influenced by internal and external sources of complexity, so-called complexity drivers. Complexity drivers have an influence on companies and the total value chain. Managing a system's complexity requires an optimum fit between internal and external complexity. Identifying, analyzing and understanding complexity drivers is the first step for complexity management's development and implementation. Complexity management is a strategic issue for companies to be competitive. For managing and optimizing company's complexity, a vast number of different single approaches is applied for different purposes. The main important strategies for single approaches' application are complexity reduction, mastering and avoidance. Complexity management requires approaches for complexity's understanding, simplification, transformation and evaluation. A successful complexity management approach enables a balance between external market's complexity and internal company's complexity. The purpose of this dissertation is to close existing gaps in scientific literature by providing a complexity management in variant-rich product development. Based on the methodology of Fink (2014), a systematic literature review was performed regarding the issues 'complexity drivers in manufacturing companies and along the value chain and their effects on company's complexity', 'application of specific single approaches and their targeted strategy', as well as 'approaches for complexity management and especially for resource planning'. An empirical research was conducted based on the methodology of Flynn *et al.* (1990) to document the current state in the German manufacturing industry regarding the issues 'complexity drivers in product development and their effects on company's complexity' and 'application of specific single approaches for complexity management'. The empirical data was collected through questionnaires between 2015 and 2016. The empirical findings are compared with literature to identify commonalities and differences. Based on literature's results, a new general approach for managing complexity in variant-rich product development was developed to bring the relevant steps for complexity handling in a sequence. It encourages the practitioner to manage product development's complexity. In this approach, complexity in product development is systematically analyzed and evaluated to create conditions for target-oriented managing and controlling of complexity. Furthermore, the general complexity management approach is modified and structurally optimized to establish a target-oriented approach for resource planning in variant-rich product development. It encourages the reader to calculate the amount of required resources over time in an early stage of a development process considering product development complexity. The new approaches are applied in the automotive industry to verify the results and approach's applicability.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AT	Automatic transmission
AWD	All-wheel drive
CG	Complexity group
DL	Derivate large
DM	Derivate medium
DoE	Design of experiments
DS	Derivate small
EP	Effort points
HV	High voltage
KPI	Key performance indicator
L	Logistics
MT	Manual transmission
N	Amount of...
OPD	Order Processing/Distribution/Sale
PC	Procurement/Purchasing
PD	Product development
PDCI	Product complexity index
PPCI	Product portfolio complexity index
PR	Production
PRCI	Process complexity index
R	Remanufacturing
RF	Resource factor
RfQ	Relevant for questionnaire
RoW	Rest of world
RQ	Research question
SC	Internal supply chain
SoP	Start of production
SUV	Sport utility vehicle
TtM	Time to market
VC	Value chain
WF	Weighting factor

1 Introduction

1.1 Motivation

„I think the next (21st) century will be the century of complexity.“
Stephen W. Hawking (1942 - 2018)

This famous statement by Stephen W. Hawking (2000, p. 29) from the year 2000 describes the current situation in science and practice. According to Maguire, Allen and McKelvey (2011, p. 1), "complexity is one of the fastest growing topics" in scientific research. In practice, the same situation can be observed. Within the last decades, complexity in manufacturing companies and especially in product development has continuously increased in many industries all over the world (Schuh, Arnoscht and Rudolf, 2010, p. 1928; ElMaraghy *et al.*, 2012, pp. 793-797; Krause, Franke and Gausemeier, 2007, pp. 3-4; Lübke, 2007, pp. 2-4; Wildemann, 2005, p. 34). The reasons are social, market-specific, technological and economical changes, such as technology innovations, dynamic environmental conditions, changing customer requirements for individualized products, market's globalization and market uncertainty. These are trends that manufacturing companies, especially in high-technology marketplaces, cannot escape and often lead to an increased complexity (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Perona and Miragliotta, 2004, p. 103; Gerschberger *et al.*, 2012, p. 1016; Mohr, Sengupta and Slater, 2010, pp. 1-5, 9-21; Voigt *et al.*, 2011, p. 1). Furthermore, markets are changing from sellers to buyers markets, caused by differentiated customer requirements and heterogeneity and the resulting necessity to create more individualized products (Wildemann, 2005, p. 34; Schuh, Arnoscht and Rudolf, 2010, p. 1928).

In today's highly competitive environment, it is fundamental for a company's success to design and bring new products quickly and with customer's individual settings to the market (Augusto Cauchick Miguel, 2007, p. 617; Lübke, 2007, pp. 2-3; ElMaraghy and ElMaraghy, 2014, p. 1). ElMaraghy and ElMaraghy (2014, p. 1) argue that "increasing global competition makes it necessary to generate wealth by being more competitive and offering goods and services that are differentiated by design and innovation". As a reaction to the increasing global competition and customer's individual needs, the companies are present in the market with a diversified product portfolio (Anderson, 2006, pp. 1-26; Caridi, Pero and Sianesi, 2009, pp. 381-382; ElMaraghy and ElMaraghy, 2014, pp. 1-2; Haumann *et al.*, 2012, pp. 107-108; Cimatti and Tani, 2009, p. 1229). In consequence, the companies cope with these trends by developing new product variants, which lead to an increased complexity in the company (Brosch and Krause, 2011, p. 1) and in product development (Kim and Wilemon, 2012, p. 1). According to Götzfried (2013, p. 31), manufacturing companies have changed their product portfolio from "standard, high-volume products to more exotic, low-volume products and product variants". Other reasons for increasing complexity in product development are the increasing number of product launches in the market, shorter product lifecycles and customer's demands for new and innovative products (Caridi, Pero and Sianesi, 2009, p. 381). According to Schaefer (1999, p. 311) and Chapman and Hyland (2004, p. 553), product development and innovation is an important key factor for business success. For company's strategy, product development became a central importance (Clark and Fujimoto, 1991, pp. 1-15; Davila, 2000, p. 383; Gupta and Wilemon, 1990, p. 24). Developing and producing individual and complex products for diversified marketplaces at minimum cost is the challenge of the 21st century (Schuh, Arnoscht and Rudolf, 2010, p. 1928; Lübke, 2007, pp. 2-4; Krause, Franke and Gausemeier, 2007, pp. 3-4; ElMaraghy *et al.*, 2012, p. 797).

One industry branch, which is characterized through high internal and external complexity, induced by an extensive product portfolio, shorter product lifecycles and customer's demands for new and innovative products with customized settings, is the automotive industry. When translating this principle to the automotive industry, for company's success and to be competitive, the automotive manufacturers have to bring innovative, individualized and complex cars in high quality and at low costs quickly to the market (Klug, 2010, p. 41). Globalization, internationalization, individualization and new technologies are reasons for the increasing product variety in the automotive industry (Klug, 2010, p. 41; Schoeller, 2009, p. 1). Furthermore, the requirements for electronical devices, safety and comfort also lead to an increase in product variety and complexity. In the strategic product planning of an automotive company, niche vehicles gain more and more importance, because new and smaller market segments have to be attended to (Klug, 2010, p. 41). Simultaneously, the innovation cycles have to be shortened due to market dynamics and lead to a further increase of complexity within the companies (Schoeller, 2009, p. 1). Another important factor that is currently being discussed is the fulfillment of legal environmental standards by the automotive manufacturers (Vogel, 2017, p. 84). Due to the growing legal and social requirements, the companies have to accept the challenge to produce environmentally friendly cars and engines. Therefore, the fulfillment of legal environmental standards becomes a competitive factor. The manufacturers are forced to ensure the environmental compatibility of their products by developing new innovations (Ruppert, 2007, p. 80). As a result of this, more and more country and technological specific parts and products have to be developed (Klug, 2010, p. 41).

As already mentioned, increasing complexity is one of the biggest tasks that manufacturing companies have to face today (ElMaraghy *et al.*, 2012, p. 793). Managing a system's complexity requires an optimum fit between internal and external complexity and comprises designing the necessary variety, handling variety-increasing factors, reducing variety and controlling complex systems (Schuh, 2005, pp. 34-35). According to Warnecke and Puhl (1997, pp. 359-362), company's complexity can only be managed if it is identified. Thus, complexity understanding becomes more and more important in manufacturing companies (Isik, 2010, p. 3683). Complexity management requires approaches for understanding, simplification, transformation and evaluation of complexity (Hünerberg and Mann, 2009, p. 3). A successful complexity management approach enables a balance between external market's complexity and internal company's complexity (Rosemann, 1998, p. 61; Kaiser, 1995, p. 17). For company's success, it is necessary to implement a complexity management in company's management process as an integrated concept (Kersten, 2011, pp. 17-18). This concerns mainly companies with an extensive product portfolio, such as automotive manufacturers. Product complexity is the main complexity factor in the automotive industry (Schoeller, 2009, p. 6). During the product development process, 80% of product's costs are defined (Bayer, 2010, p. 89). Thus, variant-rich product development is an important factor for company's business success and comes into complexity management's focus.

1.2 Research questions and objectives

The purpose of this dissertation is to develop a **complexity management for variant-rich product development**. This main purpose is subdivided into 5 sub-objectives and comprises 20 research questions, which are answered in this thesis. These research questions are separated into 14 research questions, focused on the literature research and 6 research questions, focused on the empirical research.

For an effective and target-oriented complexity management, the sources of complexity, called complexity drivers, have to be identified, analyzed and evaluated first. Further, the complexity strategies and their applied single approaches for managing complexity are identified. Next, an approach for complexity management is needed to bring the relevant steps for complexity handling in a sequence. This general approach is applied and modified for company's specific context or problem.

Following this already mentioned procedure, the **first objective** is a systematic, explicit and reproducible literature review regarding complexity drivers in manufacturing companies and along the value chain, including the fields product development, procurement/purchasing, logistics, production, order processing/distribution/ sale, internal supply chain and remanufacturing. A literature review is needed to summarize and document the state of the art in scientific literature. For this literature review, the methodology of Fink (2014, pp. 3-5) was applied and the following research questions were defined:

- RQ 1: What are the different definitions of complexity drivers that currently exist in manufacturing companies and along the value chain?
- RQ 2: What methods are applied in literature for complexity driver's identification, operationalization, and visualization?
- RQ 3: What complexity drivers occur in manufacturing companies and along the value chain?

As already mentioned, this thesis is mainly focused on product development. Based on literature review's results, the **second objective** comprises the identification and analysis of the complexity drivers in product development and their effects on company's complexity. Furthermore, it comprises a comparison of literature's results with the real world within an empirical research to document the current state in practice. The empirical research was conducted in the German manufacturing industry. Empirical research is needed to verify existing scientific knowledge and to identify commonalities and differences between literature and the real world. For this empirical research, the methodology of Flynn *et al.* (1990, pp. 253-255) was conducted. A further objective is to describe and process the perception between science and practice and their discrepancy. Before starting this empirical research, the existing literature regarding the complexity drivers and their effects, as well as the previous empirical studies, were reviewed. The following 2 research questions were formulated:

- RQ 4: What complexity drivers currently occur in the field product development in manufacturing companies in scientific literature? What effects do complexity drivers generally have on company's complexity?
- RQ 5: What empirical studies in the field complexity management currently exist in scientific literature? What objectives do they have and what research methodologies are applied? What empirical studies concern with specific complexity drivers and their effects?

Based on this literature review, the research gap was identified and 4 further research questions, focused on the empiricism, were determined to close the research gap:

- RQ 6: How is the product development of the participating companies characterized regarding product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; the height of the own value adding percentage; as well as organization's influence on product development's complexity?
- RQ 7: What are the main complexity drivers in product development and what interdependencies exist between them? Can the complexity drivers be aggregated to factors?
- RQ 8: What influences do high complexity and especially the complexity drivers have on product development's complexity?
- RQ 9: What are the significant differences and commonalities between the literature and practical (empirical) results?

After complexity driver's identification, analysis and evaluation, as well as a comparison between literature and the real world to identify commonalities and differences, the complexity strategies and their applied single approaches for managing complexity have to be identified. Furthermore, the literature results in these issues also have to be compared with the real world. This is the **third objective** of this dissertation. Before starting this empirical research, the existing literature regarding complexity strategies and the applied single approaches for managing complexity have to be reviewed. Further, previously existing empirical studies have to be identified and analyzed to get an overview about their content, objectives, research methodologies and findings and to determine the gaps in scientific research. For the literature review, the methodology of Fink (2014, pp. 3-5) was used as well and the following 3 research questions were determined:

- RQ 10: What different single approaches for complexity management currently exist in scientific literature?
- RQ 11: What focus and objectives do the existing single approaches have?
- RQ 12: What empirical studies in the field of complexity management in general and regarding specific complexity management single approaches currently exist in scientific literature?

For the empirical research, 2 further research questions were formulated to close the gaps in scientific research:

- RQ 13: What single approaches are applied for complexity management in product development and what specific complexity strategy are they focused on?
- RQ 14: What are the significant differences and commonalities between literature and the practical (empirical) results?

To bring the relevant steps for complexity handling, including complexity driver's identification, analysis and evaluation, as well as the complexity strategies and their applied single approaches, in a sequence, an approach for complexity management is needed. The **fourth objective** of this thesis is to develop a praxis-oriented approach for managing complexity in variant-rich product development, based on scientific literature. Before developing a new approach, existing literature regarding complexity management approaches has to be identified, analyzed and evaluated in detail. This forms the basis for approaches' development. For the literature review, 2 research questions were defined:

- RQ 15: What different approaches currently exist in scientific literature?
- RQ 16: What structure and focuses do the existing approaches have?

Based on the existing literature, a new and general 4-stage complexity management approach for variant-rich product development was developed. The approach is subdivided in 7 steps and is focused on product development's 3 main dimensions: Product complexity, process complexity and product portfolio complexity. For product development, especially variant-rich product development, the issue resource planning is of central importance for the company. Thus, this general approach has to be modified for company's specific context or problem. The **fifth and last objective** of this work is to generate a praxis-oriented complexity management approach for resource planning in variant-rich product development based on existing literature. Resource planning comprises the quantitative planning of human and material resources over time. For the literature review and the development of a new praxis-oriented complexity management approach, the following 4 research questions were determined:

- RQ 17: What different approaches for complexity management currently exist in scientific literature?
- RQ 18: What focus and structure do the existing approaches have?
- RQ 19: What approaches contain information about resource planning and are applicable for practice?
- RQ 20: What different stages are necessary for a praxis-oriented complexity management approach for resource planning in variant-rich product development?

As already mentioned, the purpose of this dissertation is to develop a **complexity management for variant-rich product development**. To achieve this aim, 5 sub-objectives and 20 research questions were determined and answered in the following thesis (see chapters 3 to 7).

1.3 Research process

Before starting a research project, it is necessary to define the research process. Saunders, Lewis and Thornhill (2009, p. 5) define research as "something that people undertake in order to find out things in a systematic way, thereby increasing their knowledge". Research is characterized by a systematical data collection and data interpretation to increase knowledge (Saunders, Lewis and Thornhill, 2009, p. 5). To ensure this, Saunders, Lewis and Thornhill (2009, pp. 10-11) developed a multi-stage process for conducting a research project (see Figure 1). This process is described as a series of stages, which have to be passed in a specified order. However, the precise number of stages, which are necessary for conducting a specific research project, varies. Generally, the research process starts with the formulation and clarification of the research topic (stage I) and a critical literature review (stage II). Then, the research philosophy and the approach are defined (stage III) before the research design is formulated (stage IV). Stage V is concerned with the data access and the compliance of the research ethics. Next, the data is collected and analyzed in stage VI and VII. In the last stage (VIII), the results are documented and finalized for publication. In some cases, the stages III (definition of research philosophy and approach) and V (data access and compliance of the research ethics) can be ignored.

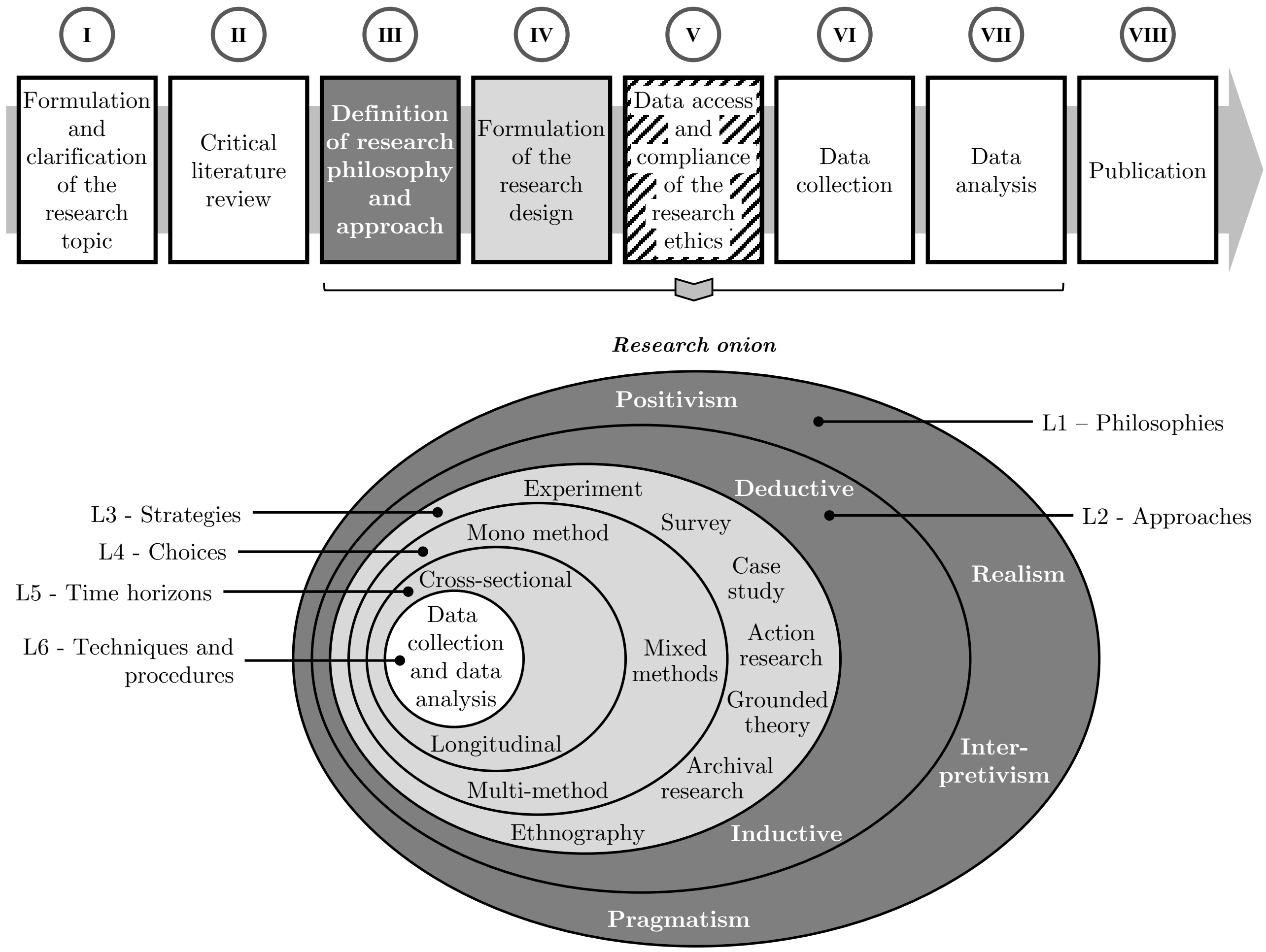


Figure 1: Research process and research onion's structure

After describing the research process, Saunders, Lewis and Thornhill (2009, pp. 106-167) developed a "research onion" with 6 different layers (L1 to L6) for the following 4 stages:

- Stage III: Research philosophies and approaches — L1, L2
- Stage IV: Formulation of the research design: Research strategies and choices, as well as time horizons — L3, L4, L5
- Stage VI and VII: Data collection and data analysis — L6

The first layer is concerned with the research philosophy and relates to the development and the nature of knowledge in a particular field. Developing knowledge is the major purpose to answer a specific problem. Research philosophy also contains important assumptions regarding researcher's view of the world and supports the researcher in the definition of the research strategy and the specific methods. The research philosophy is separated in 4 different directions according to their focus: Positivism, realism, interpretivism and pragmatism. The different directions can further be differentiated according to "researcher's view of the nature of reality or being" (ontology), "researcher's view regarding what constitutes acceptable knowledge" (epistemology) and "researcher's view of the role of values in research" (axiology) (Saunders, Lewis and Thornhill, 2009, pp. 106-108, 119).

Positivism follows the philosophical attitude of the natural scientist. The research is undertaken in a highly structured and value-free way in order to facilitate results' replication. Existing theory is used for generating the research strategy and for developing the hypotheses, which are tested and confirmed during the research process (Saunders, Lewis and Thornhill, 2009, pp. 113-114). According to Remenyi *et al.* (1998, p. 32), positivism is characterized by "working with an observable social reality" and the research's results can be generalized similar to those, which are generated by the physical and natural scientists. Besides positivism, realism is also related to scientific enquiry with the purpose of developing knowledge by using a scientific approach. However, realism is not value-free. The essence of realism is that the "reality is the truth" and "objects have an existence independent of the human mind" (Saunders, Lewis and Thornhill, 2009, p. 114). Interpretivism is characaterized through understanding the differences between humans in the role as social actors. The research is also not value-free and the results contain subjective meanings and social phenomena, because the researcher is part of the research (Saunders, Lewis and Thornhill, 2009, pp. 115, 119). For pragmatism, the most important factor is the research question. Observable information and subjective meanings are used for developing acceptable knowledge to answer the research question (Saunders, Lewis and Thornhill, 2009, p. 109).

The second layer is also a part of stage III and decribes the 2 different research approaches, which are applied for scientific research: Deductive research and inductive research. Deductive research is focused on testing an existing theory from literature and is associated to the research philosophy positivism. In contrast, inductive research is focused on building new theories based on collected data and is associated to interpretivism. The deductive research is predominantly used in the natural sciences and characterized by using highly structured approaches, developing and testing of hypotheses based on quantitative data and explaining of causal relationships between different variables. Further important characteristics are the operationalized concepts for quantitive measurement of the data and the generalization of the results. The researcher is not a part of the researched field. The inductive research is characterized through qualitative data and the development of an understanding regarding a specific research context. Gaining an understanding of humans' meanings and an understanding, why something is happening, is in the focus. In contrast, results' generalization is less important and out of focus. The research structure is more flexible and the researcher is a part of the research process. Thus, the inductive research process is much longer regarding the time period and riskier than a deductive research process (Saunders, Lewis and Thornhill, 2009, pp. 124-127).

Another important part of the "research onion" is the research design (stage IV) with the layers 'research strategies' (L3), 'research choices' (L4) and the 'time horizons' (L5). The research design is a general plan for answering the research questions. Before formulating the research design, it is necessary to define the purpose of the reseach project. In literature, 3 different classifications of research purposes exist and are used for answering the research questions: Exploratory, descriptive and explanatory (Saunders, Lewis and Thornhill, 2009, pp. 136-139). An exploratory study is characterized through valuable means and is often used to find out, what happened or to get a new insight in something (Robson, 2002, p. 59). Exploratory studies are very flexible and adjustable to change and can be conducted by reviewing the literature, interviewing experts or by conducting focus group interviews. Descriptive studies are applied for describing situations, events or profiles of persons. Before starting a descriptive study, the researcher needs a clear picture of the phenomena on which the data is collected. Explanatory studies are characterized through the explanation of causal relationships between different variables regarding a situation or problem. The relationships can be identified by analyzing quantitative or qualitative data. The quantitative data is analyzed by statistical tests to identify the relationships. In contrast, qualitative data is analyzed by explaining the reasons, why something has happened (Saunders, Lewis and Thornhill, 2009, pp. 139-141).

After selecting the research purpose, it is necessary to identify the appropriate research strategy. In literature, several research strategies exist and are described. However, the strategies are often related to a specific research purpose and the choice of a specific strategy is related to the research questions and objectives. The following strategies are applied in scientific research: Experiment, survey, case study, action research, grounded theory, ethnography and archival research. Detailed information about these strategies is described in the publications of Saunders, Lewis and Thornhill (2009, pp. 141-151) and Robson (2002, p. 178).

In the next layer, different research choices (L4) are described. In scientific research and especially in business and management research, 2 types of data exist: Quantitative and qualitative data. Both terms are often associated with their data collection techniques and data analysis procedures. Generally, quantitative data is numerical data (numbers), which is collected for example through questionnaires and analyzed by statistical methods. In contrast, qualitative data is non-numerical data (words), which is collected for example through interviews and analyzed by data categorizing. The research choice is characterized through the combination of quantitative and qualitative data collection techniques and analysis procedures. In literature, the research choice can be separated in 'mono method' and 'multiple methods'. Mono method uses only 1 data collection technique and analysis procedure: Quantitative (e.g. questionnaire) or qualitative (in-depth interviews). In contrast, multiple methods "use more than one data collection technique and analysis procedures to answer the research question" (Saunders, Lewis and Thornhill, 2009, p. 151). Multiple methods can be further separated in 'multi-methods' and 'mixed-methods'. Using more than one quantitative or qualitative data collection technique and analysis technique during the research process, is a multi-method study. Mixed-method research "uses quantitative and qualitative data collection techniques and analysis procedures either at the same time (parallel) or one after the other (sequential) but does not combine them" (Saunders, Lewis and Thornhill, 2009, p. 152).

After defining the research choice and before starting the data collection, the researcher has to determine the time horizon (L5). This is also an important part of the research process and its planning. Generally, the time horizon is independent from the research strategy and the applied methods. In scientific research, 2 different time horizons exist: Cross-sectional and longitudinal. Cross-sectional researches study a specific phenomenon at a particular time, like a "snapshot". For these studies, a survey strategy is often used. In contrast, longitudinal studies have a "diary" perspective with the purpose of studying changes and/or developments over a period of time (Saunders, Lewis and Thornhill, 2009, pp. 155-156).

Before starting the data collection (stage VI) and data anlysis (stage VII), the data access and the compliance of the research ethics are checked. Gaining access to an appropriate source is important for collecting primary or secondary data. The suitability of a data source depends on the research question, the objectives and the research design. In literature, 2 different kinds of access are described for answering the research question(s): Physical access (e.g. to an organization) or cognitive access (e.g. representative sample of participants or secondary data). When conducting a research project, the researcher has to think carefully about ethical concerns regarding data access, as well as data collection, analysis and reporting before starting the research. During the last years, the ethics of research pratice have increased strongly (Saunders, Lewis and Thornhill, 2009, pp. 168-172; 183-184).

In the next step, the data has to be collected (stage VI) and analyzed (stage VII). After analyzing, the results have to be published (stage VIII). Data collection and analyzing is a vast field and will not be explained in detail in this section. Further information about these 2 topics can be gathered from the publication of Saunders, Lewis and Thornhill (2009).

In this dissertation, the research process from Saunders, Lewis and Thornhill (2009) is used for structuring the research project. In the first stage, the research topic is formulated and clarified. As already mentioned, complexity in manufacturing companies and especially in product development has continuously increased within the last years. The reasons are market's globalization and uncertainty, technological and economical changes, as well as changes in customer requirements for individualized products, which have to be developed. Manufacturing companies cannot escape these trends. Thus, a complexity management in manufacturing companies and especially in variant-rich product development is necessary to be competitive. The following research topic is definied as the title of this dissertation: Complexity management in variant-rich product development.

In the next stage (stage II), the relevant literature is reviewed to describe the current state of the art and to identify research gaps in existing scientific literature. For the literature reviews, the methodology of Fink (2014, pp. 3-4) was used. Fink (2014, pp. 3-4) divides a literature review into 7 tasks (1 to 7), starting with the definition of the research questions (1) and the selection of the required sources (2), such as bibliographic or article databases, web sites and other sources to identify relevant literature. Then, the search terms are defined (3). The search terms are based on the words that frame the research questions, including all relevant synonyms and paraphrases. To increase research's quality, the databases and search terms should be checked by other experts or researchers. In the next step, practical (4) and methodological (5) screening criteria are defined and applied to identify (6) and select (7) the relevant literature from the entity of found literature.

According to Fink (2014), 14 research questions, focused on reviewing the existing literature, are formulated in this thesis (see section 1.2). To extend the amount of relevant literature, the literature research was conducted in English- and German-language literature and databases. The following 8 English and German databases were used: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink. The databases were defined through an iterative cycle, starting with 1 database. During the research process, some literature sources were found in other specific databases. Thus, these databases were also included in the research process. The literature search was performed within a "particular grammar and logic" (Fink, 2014, p. 3). The key words and their synonyms, as well as other terms were combined with Boolean operators, such as AND, OR, NOT and NEAR. Generally, the application of Boolean operators depends on the specific database. The finalized search terms were also identified through an iterative cycle, starting with 1 key word and adding more in the process of research in order to summarize all necessary and possible literature and results (Saunders, Lewis and Thornhill, 2009, pp. 75-78). Furthermore, the search terms are defined in English and German and then formulated more general to extend the results and to prevent the elimination of important articles (see Tables 1, 34, 45 and 48). The search resulted in a certain amount of literature sources, including research papers from journals, conference proceedings, working papers, books, essays and PhD theses, but only a few are relevant. In addition, several literature sources were found repeatedly. Consequently, it was necessary to screen and synthesize the results. The searched literature was analyzed, evaluated and synthesized based on the qualitative content analysis and the aforementioned research questions to identify the relevant literature sources. Within the qualitative content analysis, the information was extracted, formatted and evaluated. For analyzing and synthesizing the literature, different categories were defined based on the research questions. During the analyzing and synthesizing process, the categories were altered and new ones were added. Then, the categories were implemented in a synthesis matrix to organize and assign the identified literature and their different contents. Sources without focus on manufacturing companies or the value chain were not considered. The results from the different literature sources were compared to identify commonalities and differences. The literature reviews were closed by identifying scientific gaps (see section 2.2) and result's documentation. To compare the results from literature with empirical findings, the time period for the different literature researches was restricted between 1900/01/01 and 2015/12/31, because the empirical study was performed in the years 2015 and 2016.

After reviewing the relevant literature, the research philosophy and the research approach are defined. In literature, 4 different research philosophies are mentioned for developing knowledge in a particular field: Positivism, realism, interpretivism and pragmatism. Further, 2 different approaches are applied for scientific research: Deductive research and inductive research. For this dissertation, the research philosophy positivism is followed to develop additional knowledge regarding complexity management in variant-rich product development. Positivism is characterized through a highly-structured and value-free research to facilitate results' replication and generalization. Existing literature is used as a basis for this research. Regarding research's approach, the deductive research is applied in this thesis to test existing theories and knowledge from literature based on quantitative data and highy structured approaches. Causal relationships between different variables are explained and the results are generalized. In summary, the research philosophy positivism and the deductive approach can be recognized in all main parts of this thesis (see chapter 3 to 7).

In the next stage (stage IV), the research design is formulated, starting with the research strategy. Then, the research choice and the time horizon are determined. In this dissertation, the research strategy 'survey' is applied to collect quantitative data regarding 'complexity drivers in product development and their effects on company's complexity' and the 'application of specific single approaches for complexity handling' from the manufacturing industry of Germany, by using a questionnaire. The data is analyzed with descriptive statistics (see chapter 4 and 5). The research purpose is a combination of descriptive and explanatory. In this thesis, the complexity situation and phenomenon in the manufacturing industry of Germany are described and the causal relationships between different variables are explained. Regarding the research choice, only quantitative data is collected and analyzed in this study (mono method). Further, the time-horizon cross-sectional is used in this dissertation to study the complexity situation and phenomenon within the German manufacturing industry at a particular time. The survey strategy in combination with collecting quantitative data at a cross-sectional time horizon is often applied in business and management research.

Before starting the data collection, the data access and the compliance of research ethics are checked (stage V). For the survey in this disseratation, the Amadeus database was used as the data source (cognitive access). In the Amadeus database, all manufacturing companies of Germany from different fields of industry are documented at a particular time. Regarding research ethics, the ethical concerns regarding data access, as well as data collection, analysis and reporting are considered during the research process.

Next, the data is collected (stage VI) and analyzed (stage VII) before publication (stage VIII). In this thesis, an empirical study was used to document the current state in the manufacturing industry of Germany regarding the issues 'complexity drivers in product development and their effects on company's complexity' (see chapter 4) and the 'application of specific single approaches for complexity handling' (see chapter 5). The empirical findings were compared with the literature to identify commonalities and differences. The empirical research was conducted based on a 6-stage systematic approach (I to VI), which was developed by Flynn *et al.* (1990, pp. 253-255). The approach starts with the determination of the theoretical foundation (I) and the research design (II). Then, the data collection method is selected (III). The data collection method, which is mostly used in scientific research, is the questionnaire. It is a useful technique for single and multiple case studies, as well as panel studies and focus groups. In stage IV, the data collection methods and sample description for research's implementation are selected. Before preparing the research report for publication (VI), the collected data is processed and analyzed in stage V (Flynn *et al.*, 1990, pp. 253-268). Following the methodology of Flynn *et al.* (1990), 6 empirical research questions (see section 1.2) were defined in the first step. Then, the research design 'survey' was selected. For data collection, a standardized questionnaire with 16 questions and a fixed response possibility was applied in this research. The questions were formulated based on the research questions and the questionnaire was structured in 4 main parts: General information regarding the respondents (company size, field of industry and respondent's position in the company); general information about product development's characteristics (dimension of product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; as well as the height of the own value adding percentage), information about the complexity drivers and their effects and the application of specific single approaches for complexity handling. The data was collected from a stratified random sample, which was taken out of a given population of 17,862 manufacturing companies, located in Germany with more than 50 employees. In 2015 and 2016, the questionnaire was sent by e-mail to 3,086 companies in 2 stages, exclusive of service and printing companies. Before starting this empirical research, a first version of the questionnaire was pretested by 40 experts from the potential target group to check and refine the wording, understanding, relevance, as well as the measurement instrument. Furthermore, questionnaire's length and the time for questionnaire's responding was checked. Based on pretest's results and comments from the experts, the questionnaire was revised and checked again by a smaller group of experts. For answering the empirical research questions, the empirical data was analyzed by using statistical data analysis techniques from the groups descriptive statistics (e.g. means, frequencies and proportions), measures of dimensionalities (e.g. factor analysis) and statistical interpretation of parameters (correlation analysis). In the last stage (stage VIII), the results are summarized and documented.

1.4 Contribution for science and practice

The contribution of this dissertation is to gain additional knowledge for science and practice based on literature and empirial research by describing what is currently known in literature and practice on the following issues:

- Complexity drivers in manufacturing companies and along the value chain, especially in product development and their effects on company's complexity.
- Complexity strategies and their applied single approaches for managing complexity.
- Approach(es) for complexity management, especially in variant-rich product development.
- Complexity management approach for resource planning, especially in variant-rich product development.

A further contribution is to answer manager's questions regarding the different issues and to compare the empirical findings with literature to identify commonalities and differences. In additon, this dissertation closes currently existing gaps in literature regarding the aforementioned issues and gives implications for future research.

From **scientific perspective**, the different literature reviews, which were performed in this thesis, present a current state of the art about the already mentioned issues and give the researcher a first insight and general understanding about the different topics before starting a research project in this field. Furthermore, existing gaps in literature are pointed out. Prinicipally, the literature reviews can be used for further dissertations or research proposals to give an overview about the specific issue and are helpful for other researchers, who have no prior knowledge in this field. Based on these reviews, researchers can build new ideas and theories for their own research. Further, it helps the researcher to avoid time-wasting and research effort by "reinventing the wheel". In this thesis, the research methodologies regarding the different issues, including research questions, databases and synthesizing methods are described in detail to increase transparency and traceability. This enables the researcher to reproduce the findings. The literature reviews provide a comprehensive survey of significant literature and their results on the different issues based on analyzing, synthesizing and summarizing the existing literature. Regarding the issue complexity drivers, the different literature sources and the trends of complexity drivers in literature and in the different fields (general in manufacturing companies and/or along the value chain, especially in product development) over the last 25 years are described. The trends show the researcher how essential the topic complexity drivers is in literature and that it is thus interesting for future research. Furthermore, different definitions of complexity drivers are analyzed and described. Based on this result, a new overall definition of complexity drivers is presented. In addition, the existing approaches for complexity driver's identification, operationalization and visualization are identified and specified according to their focus. The identified complexity drivers are clustered in aggregated complexity driver's main categories according to their characteristics to provide a general classification system without overlaps. Further, the effects of high complexity, which are induced by the complexity drivers, are described and classified based on literature. A new general framework for complexity effect's identification, analysis and evaluation in the company and along the value chain is generated and presented for other researchers. Regarding the issue complexity strategies and their applied single approaches for managing complexity, this thesis presents the researcher an overview about the existing single approaches and their targeted strategies, which are described in literature by different authors. According to the approaches for complexity management in variant-rich product development and for resource planning, an overview about the existing complexity management approaches in the company and in different fields along the value chain, including the analysis of approaches' structure, targets and applicability for resource planning, is presented. Based on these results, a new general approach for complexity management in variant-rich product development and for resource planning is generated and provided for other scientific researchers.

As already mentioned, a further contribution of this dissertation is to gain additional knowledge for science and practice based on empirial research. From scientific perspective, the empirical researches establish a connection between scientific research and practice within a systematical and target-oriented data collection and allow the researcher an insight in the real world. The empirical studies give the researcher an overview about what is already known in practice and practice's tendencies about the issues complexity drivers in product development and the application of specific complexity management single approaches. It closes a currently existing gap in scientific literature by comparing the literature and empirical results to identify similarities and differences and to verify scientific findings. Based on this comparison, the theoretical findings can also be confirmed, advanced or progressed within the empirical researches, which are presented in this thesis. Furthermore, the researcher gains some detail information about the research and data collection methodology, the objectives and the sample description to increase transparency. This enables the researcher to reproduce the findings. Based on the empirical findings, researchers can build new ideas, theories and hypotheses for their own research. Regarding the empirical research about the application of specific complexity management single approaches, the empirical research shows that in practice the application of a specific complexity management single approach depends on the situation and complexity problem, as well as the desired strategy. Thus, the approaches cannot be assigned to 1 specific strategy, contrary to the current opinion in scientific literature.

From **practical perspective,** this dissertation and the presented literature reviews give the practitioner a first insight and understanding about the different aforementioned issues and their importance. The result of different scientific researches was that companies are aware of complexity and some of its causes, but they often do not know how to handle it, because of a lack of specific methods or tools. Thus, different methods or tools for complexity handling are described in this thesis, including for complexity driver's identification, operationalization and visualization, as well as an overall selection of specific single approaches for managing complexity and their targeted strategy. Beyond, the practitioner gets an overview about different approaches for complexity management and their focuses, which were developed by other authors and for different fields along the value chain. Based on these approaches, a new general approach for complexity management in variant-rich product development and resource planning is developed and provided for the practitioners, including the structure, targets and focus. Thus, the practitioners can choose the right method, tool or approach for solving their complexity task or problem. Furthermore, this thesis answers manager's questions concerning the different issues. Regarding complexity drivers and their effects on company's complexity, the following manager's questions "What are complexity drivers?", "Why they are so important for me?", "What effects do they have on my/our/company's complexity?", "How can I identify, operationalize and visualize complexity drivers?" and "What are important complexity drivers in the field of product development?" are answered by providing an overall definition about complexity drivers and an overview about existing approaches for complexity driver's identification, operationalization and visualization. In addition, a list of theoretical existing complexity drivers and their effects on company's complexity, which were found in literature, are described, so the management has a general overview about complexity drivers and their effects and can compare these findings with their own complexity drivers to identify commonalities and differences, as well as get a first indication. Further manager's questions regarding the application of different single approaches for managing complexity are also answered in this work: "What are single approaches for complexity management?", "What different single approaches exist?" and "What is their focus and targeted strategy?". Therefore, a general description for a complexity management single approach is given and the different single approaches, which exist in scientific literature, are described, including their focus and targeted strategy. Regarding the issue approaches for complexity management and resource planning, the following manager's questions are also answered: "What different approaches for complexity handling and resource planning exist?", "On what situation or on what field in the company and along the value chain are they focused?", "What structure or stages and targets do they have?", "What approaches comprise the quantitative planning of human and material resources over time?" and "Are the approaches applicable for resource planning in product development?". Thus, an overview about the different approaches for complexity management and resource planning, including their structure, targets and focus, is presented.

As already mentioned in the category scientific perspective, a further contribution of this dissertation is to increase additional knowledge for science and practice based on empirial research. From practical perspective, the first empirical study gives the practitioner an overview about complexity perception by other practitioners, especially in the field product development. Furthermore, the practitioner receives a differentiated overview of complexity in product development, which is perceived in different fields of industry. The studies also answer the following manager's questions "What complexity sources (drivers) have a high influence on product development's complexity and are thus relevant for the company?" and "What effects does high complexity within the company have on product development?", by providing an overview about the main and relevant complexity drivers, which were assigned by the respondents with a strong or very strong influence on product development's complexity. Beyond, the practitioner gets an overview about the main topics and properties in product development with high complexity, which have a strong or very strong influence on product development's performance as said so by the respondents. This overview can increase transparency for the practitioner. Regarding the single approaches for complexity management, the second empirical study gives the practitioner an overview about the different approaches for complexity management and their focus and targeted strategy. Further, this study also answers the following manager's questions "What different approaches are used by other practitioners in other fields of industry?" and "What focus or strategy is pursued by other practitioners in other fields of industry by using a specific single approach?" by providing an overview about the complexity management single approaches and their main focus or strategy. However, a specific recommendation regarding the application of a specific single approach cannot be given, because the selection and application of a specific approach and strategy depends on company's situation or complexity problem. However, this empirical research helps the practitioners to find the right approach for their specific situation or complexity problem.

1.5 Structure of the thesis

The present dissertation is subdivided into 8 chapters (see Figure 2), starting with the introduction, the basics and a literature review. The introduction contains the motivation, the research questions and objectives, the research process, as well as the contribution for science and practice.

In chapter 2, the issues complexity management, product development, as well as resource planning are described and gaps in scientific literature are pointed out. The fundamentals and basic definitions according to complexity and complexity management are presented. Further, the sources of complexity, called complexity drivers and their effects on company's complexity, as well as the strategies and the applied single approaches for managing complexity are described. Next, the current state of the art regarding complexity management approaches is pointed out. Regarding product development, product development's characterization and objectives along with its phases are described. Furthermore, the reasons for complexity in product development and the importance of resource planning in product development are described. At the end of chapter 2, the gaps in scientific research regarding the 3 aforementioned issues are presented.

For an effective complexity management, the sources of complexity have to be identified, analyzed and evaluated first. Further, the complexity strategies and their applied single approaches for managing complexity are identified. Next, an approach for complexity management is needed to bring the relevant steps for complexity handling in a sequence. This general approach is applied and modified for company's specific context or problem. The chapters 3 to 7 concern the mentioned procedure and answer the above-mentioned research questions.

In chapter 3, a literature review regarding complexity drivers in manufacturing companies and along the value chain is described. The chapter starts with an introduction and the research method, including the research methodology and questions, the boundary definition, as well as the research segmentation and overview. Some definitions of literature reviews are disclosed and a framework for constructing a literature review is specified. Next, the literature review about complexity drivers, including the results of the literature research, is described, starting with the analysis, classification and segmentation of the identified literature sources according to their content and objectives and to identify gaps in scientific literature. The trend of all literature sources about complexity drivers in a specific period of time is presented. Furthermore, an overview about different definitions for complexity drivers and approaches for complexity driver's identification, operationalization and visualization is presented. A new general and extensive definition for complexity drivers is generated based on literature's findings to close this literature gap. The new definition summarizes all information from already existing definitions and is applicable general in manufacturing companies, as well as in all parts along the value chain. The most discussed complexity drivers in manufacturing companies and along the value chain are described and classified in a new general and extensive classification system. The new classification system is created in a superior way without overlaps between the different complexity driver categories and based on existing classification systems to close the existing gap in literature. In addition, this classification system can be applied general in manufacturing companies and in all parts along the value chain. All complexity drivers, which occure in the company and along the value chain, can be allocated to this superior classification system. Finally, implications for future research are highlighted.

To verify existing scientific knowledge and to identify commonalities and differences, the results from literature are compared with the real world within an empirical study. Chapter 4 presents an empirical research regarding complexity drivers in product development and its comparison with literature. It starts with an introduction and a literature review about complexity drivers in product development and their effects on company's complexity. Furthermore, an overview about existing empirical researches in the field complexity management in a specific period of time is described to identify gaps in literature. Previous empirical studies regarding complexity management are focused on various issues and refer to different fields along the value chain. However, an empirical study in the field product development and with focus on complexity drivers and their effects on company's complexity does not exist yet. To close this gap in literature and to identify practice's knowledge and tendencies about this topic, a new empirical research in the German manufacturing industry was conducted. Next, the research methodology and objectives, questionnaire's design, as well as the data collection methodology, sample description and the statistical analysis, including research's limitations, are presented. The empirical findings regarding complexity drivers in product development and their effects on company's complexity, as well as the sample results are described. The complexity drivers are aggregated based on a correlation and factor analysis to identify the most important factors, which reflect more than 50% of the complexity drivers in product development. These factors are important for a target-oriented complexity management in product development. In addition, the empirical results are compared with literature to identify commonalities and differences, as well as to verify existing scientific findings. Based on this comparison, the theoretical findings are confirmed, advanced and progressed. In the end of chapter 4, the research questions are answered and implications for future research are pointed out.

After complexity driver's identification, analysis and evaluation, the complexity strategies and their applied single approaches for managing complexity come into focus. In chapter 5, an empirical research about single approaches for managing complexity in product development and their objectives is presented and starts with the introduction and a literature review. The literature review presents an overview about the different single approaches, which are applied for managing company's complexity and their objectives. Furthermore, the existing empirical researches in the field of complexity management are described and analyzed to identify gaps in literature. As already mentioned, previous empirical studies are focused on various issues and refer to different fields along the value chain. However, none of the existing studies concern with specific single approaches and their targeted strategy for complexity management in product development. Furthermore, the previous studies do not compare their results with the literature to identify commonalities and differences and to verify scientific findings. Closing this gap is the aim of the new empirical study. In the next step, the empirical research is described in detail by presenting the research methodology and objectives, questionnaire's design, as well as the data collection methodology, sample descriptions and the statistical analysis. Next, the empirical findings are described. In the first part, the sample results and the data validation are presented.

Data validation is important for distortions' avoidance and to ensure that the empirical findings are representative for generalization. The second part gives an overview about the results and practice's knowledge and tendencies regarding the single approaches for managing complexity and their targeted strategies. In the last part, the empirical findings are compared with the existing literature to identify commonalities and differences. Based on this comparison, the theoretical findings are also confirmed, advanced and progressed. Chapter 5 is closed by answering the research questions and with implications for future research.

As already mentioned, a further important part of an effective complexity management in a company is a specific approach for complexity management, which includes all relevant steps for complexity handling in a sequence. Chapter 6 presents a new general approach for complexity management in variant-rich product development, which is developed based on existing literature and applied in the automotive industry to verify the new general approach. At the beginning of chapter 6, a literature overview about complexity management, its properties, requirements and objectives, as well as the research methodology are described. Furthermore, an overview of existing complexity management approaches in different fields is presented. The previous approaches are analyzed according to their focus, structure and targets. Further, they are evaluated based on several requirements, which are necessary for a general complexity management approach in variant-rich product development, to identify strengths, weaknesses and deficits. As a result of the evaluation process, no approach fulfilled all requirements and consisted of all stages and categories. To close this gap in scientific literature and to combine all strengths in one superior approach, a new general approach for complexity management in variant-rich product development is developed and described based on the existing complexity management approaches. To verify the results, the new approach is applied on a recent development project in the automotive industry, because this industry branch is characterized through an extensive product portfolio and complexity. In the end of chapter 6, implications for future research are pointed out.

Depending on company's specific context, objective or problem, the general approach from chapter 6 has to be modified. In chapter 7, a complexity management approach for resource planning in variant-rich product development is developed based on literature. Complexity management and resource planning are important issues for company's success and competitiveness. Chapter 7 starts with introduction and a literature overview about the properties, requirements and objectives in the issues complexity management, product development and resource planning. Furthermore, an overview of existing complexity management approaches and their applicability for resource planning in different fields is presented. The existing approaches are also analyzed and evaluated according to their focus, structure and targets. As a result of the analysis and evaluation process, only one approach is identified, which fulfills all requirements and consists of all stages. However, the order of the different stages was not feasible in practice for resource planning in variant-rich product development. Therefore, a new and structurally optimized complexity management approach for resource planning in variant-rich product development is developed and described based on the general approach from chapter 6, to increase the practicability in practice. The new approach is also applied on a recent development project in the automotive industry, focused on alternative hybrid powertrains, to verify the results and the practicability in practice. Finally, the research gap is closed with implications for future research.

Chapter 8 summarizes the thesis by answering the overall research questions. Furthermore, the limitations and implications for future research are pointed out.

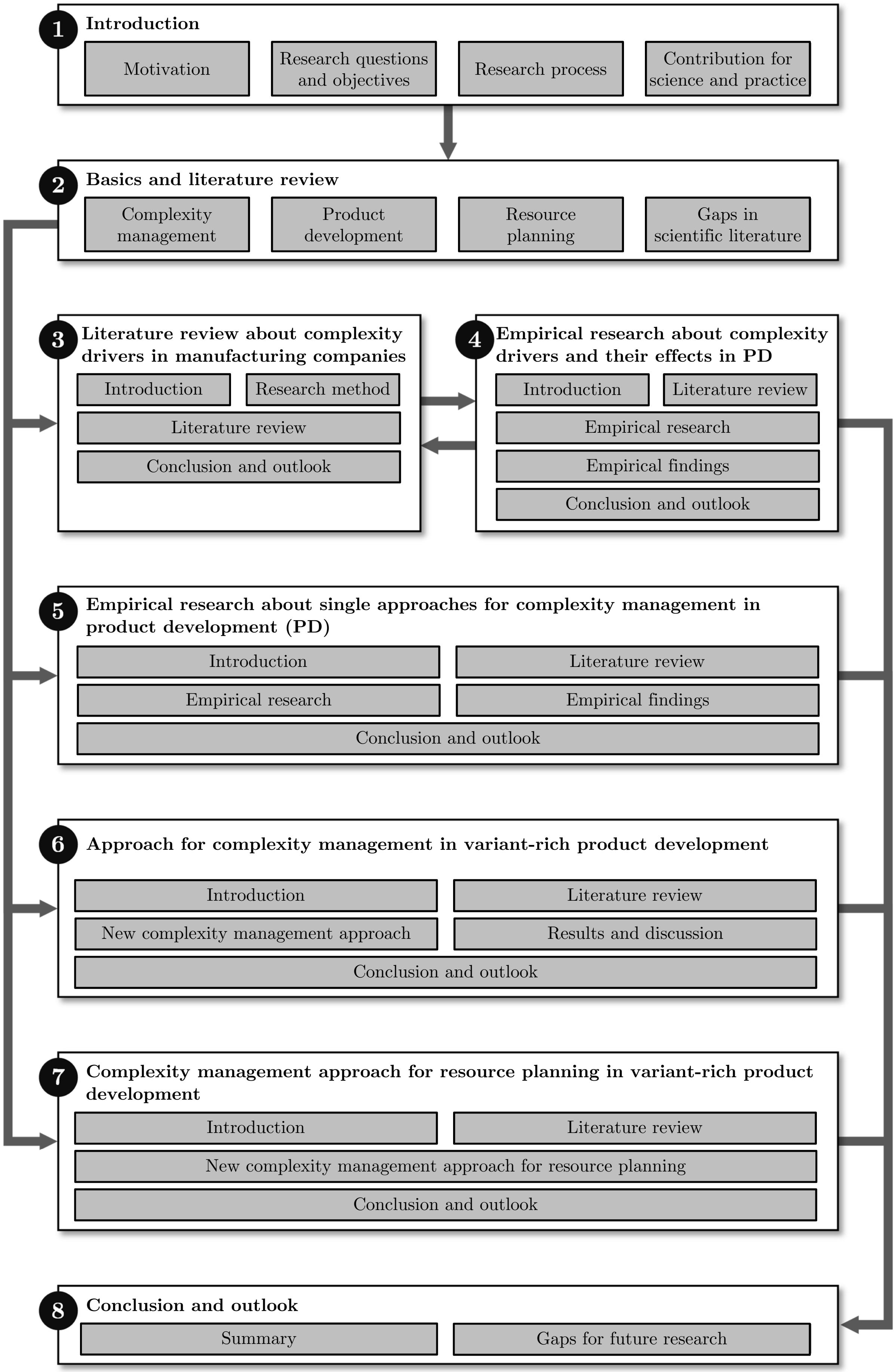


Figure 2: Structure of the thesis

2 Fundamentals and literature review

Regarding the title of this thesis "Complexity management in variant-rich product development", chapter 2 presents the basics about the issues complexity management and product development in a summarized form and refers to other parts of this thesis (see chapter 3 to 7). Further, the basics for the issue resource planning are described in this chapter, because resource planning is also an important issue for variant-rich product development and company's complexity management. Detailed information about these 3 issues and the literature sources, which are used for the different literature reviews, are decribed in the chapters 3 to 7.

2.1 Basics

2.1.1 Complexity management

As already mentioned in the introduction, complexity is the paradigm of the 21st century (Hawking, 2000, p. 29). Complexity has been discussed in several fields of research, such as "physics, biology, chemistry, mathematics, computer science and economics" (Isik, 2010, p. 3682). The origin of the term complexity comes from the Latin words "complexus" and "complecti", which means "extensive, interrelated, confusing, entwined or twisted together" (ElMaraghy *et al.*, 2012, p. 794; Pfeifer *et al.*, 1989, p. 889). The Oxford Dictionaries (2014) define "complex" as follows: Something is complex if it is "consisting of many different and connected parts" and it is "not easy to analyze or understand". Complexity is directly connected with a system and its terminology (Ulrich, 1970, pp. 115-117; Prillmann, 1996, pp. 57-58).

Based on systems theory, complexity is characterized by the amount and diversity of system's elements, the amount and type of relations and dependencies and the variation of the elements and their dependencies over time (Luhmann, 1980, pp. 1064-1065; Kersten, 2011, p. 15). According to Ulrich (1970, pp. 115-117), the elements and their relations are significant for system's complexity. In dynamic systems, the system can adopt a high amount of different conditions. Schuh (2005, pp. 34-35) follows Ulrich's argumentation and characterizes complex systems by the variety of their states. Further, a system is always surrounded by an environment and can be isolated by the system boundary (Skirde, 2015, p. 10). However, the system and its complexity are influenced by the environment (Ulrich, 1970, pp. 105-107, 112).

In scientific literature, there is no general understanding of the term "complexity". Many different definitions for the term "complexity" are presented, because the meaning is vague and ambiguous. An explicit, universal and widely accepted definition does not exist (Brosch and Krause, 2011, p. 2; ElMaraghy *et al.*, 2012, p. 794). As a result, the term "complexity" is often used synonymously with the term "complicated" (Gießmann, 2010, p. 30), but the terms have specific characteristics and different meanings. Generally, complexity is "in the eye of the beholder" (Meijer, 2006, p. 1). Complexity is driven by individual's sensation and perspective, as well as experience and knowledge. What is complex to someone, might not be complex to another (Leeuw, Grotenhuis and Goor, 2013, p. 961).

There are 2 types of complexity: Good and bad. The good type of complexity is necessary. It helps a company to gain market shares and is value adding. On the other hand, bad complexity brings little value, reduces revenue and causes excessive costs (ElMaraghy *et al.*, 2012, p. 811; Isik, 2010, p. 3681). Increasing complexity is often related to increasing costs (Meyer, 2007, p. 94). Complexity is a phenomenon and evolutionary process, which presents a challenge, especially for science and engineering. Complexity is characterized through change, choice and selection, as well as perception and progress. Furthermore, complexity is intensified through innovations in products and processes (Warnecke, 2010, p. 639). Increasing complexity is one of the biggest challenges that manufacturing companies have to face today (ElMaraghy *et al.*, 2012, p. 793).

Generally, complexity is caused by internal and external factors, called complexity drivers (Meyer, 2007, pp. 26-27). Complexity drivers are factors, which influence a system's complexity and are responsible for increasing system's complexity level (Meyer, 2007, p. 26). They can cause turbulences and new functional models in a system (Krizanits, 2015, p. 44). Complexity drivers play a significant role for complexity management, because they describe a system's complexity and help to evaluate and handle it (Vogel and Lasch, 2015, pp. 98-99). According to Erkayhan (2011, p. 2), complexity drivers are the main adjusting levers for improvements of the company's success.

In principle, complexity drivers can be separated in internal and external drivers according to their origin (Blecker, Kersten and Meyer, 2005, pp. 48-51). Internal complexity drivers describe the company's complexity and can be influenced actively by the company itself (Bliss, 2000, pp. 4-7; Kersten *et al.*, 2006, p. 326). External complexity drivers are factors, which influence company's complexity directly from outside (Wildemann, 1998, pp. 47-52; Kersten *et al.*, 2006, p. 326). External complexity drivers are constant and cannot or nearly cannot be influenced by the company itself, because they are not induced by the company (Kersten *et al.*, 2006, p. 326; Gießmann and Lasch, 2011, pp. 4-6). The internal and external complexity drivers are connected directly and cannot be separated selectively and operationalized (Größler, Grübner and Milling, 2006, p. 256; Belz and Schmitz, 2011, pp. 185-186; Collinson and Jay, 2012, pp. 7-8). Bohne (1998, pp. 58-59) and Klepsch (2004, pp. 7-9) describe that external complexity produces internal complexity as a reaction. In addition, the internal complexity drivers can be differentiated in correlated and autonomous drivers. Correlated complexity drivers have a direct correlation to the external market's complexity and are influenced by it. Autonomous complexity drivers are not influenced by external factors. They are determined by the company itself (Bliss, 1998, pp. 147-148).

Complexity drivers have an influence on companies and the total value chain (Schuh, 2005, pp. 8-19). Further, complexity drivers are responsible for complexity costs (Greitemeyer, Meier and Ulrich, 2008, pp. 37-38). Keuper (2004, pp. 82-83) describes that handling a company's complexity depends on the complexity drivers. Thus, complexity management in the company requires identification and controlling of the essential complexity drivers (Schuh, 2005, p. 8; Budde and Golovatchev, 2011, p. 2) and the effects of high complexity (Kersten, Koppenhagen and Meyer, 2004, pp. 211-214) on the categories time, quality, costs and flexibility. Identifying, analyzing and understanding complexity drivers as main elements related to complexity are the first step to develop and implement a clear strategy to handle complexity (Miragliotta, Perona and Portioli-Staudacher, 2002, pp. 384-388; Serdarasan, 2011, p. 792). Without an idea of complexity drivers, it would be difficult to develop an effective complexity strategy (Serdarasan, 2011, p. 792). Heydari and Dalili (2012,

p. 64) argue that a researcher in complexity management needs to know, what the key drivers of complexity in a system are. In literature, several approaches for complexity driver's identification, operationalization and visualization exist (see subsection 3.3.3).

Complexity management is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383; Budde and Golovatchev, 2011, p. 2). Managing a system's complexity requires an optimum fit between internal and external complexity and comprises 4 tasks: Designing the necessary variety, handling variety-increasing factors, reducing variety and controlling complex systems (Schuh, 2005, pp. 34-35). Furthermore, complexity management comprises a target-oriented complexity design (Meyer, 2007, p. 25). According to ElMaraghy *et al.* (2012, p. 809), complexity management is a business methodology with the objective of complexity analysis and optimization within a company.

For managing and optimizing company's complexity, a vast number of different single approaches are described in literature (Gießmann, 2010, pp. 57-70). Single approaches are methods or tools, which are used for structuring or dealing with a task, situation or problem (Oxford Living Dictionaries, 2017a; Dictionary, 2017; Kieviet, 2014, pp. 2, 44). They are focused on specific objectives and strategies to solve a problem in the company and to achieve a long-term or overall aim (Lindemann and Baumberger, 2006, p. 9; Cambridge Dictionary, 2017; Oxford Living Dictionaries, 2017b). Approach's application depends on the particular situation and must be planned company-specific (Gießmann, 2010, pp. 57-70). In literature, there is no specific instruction, which approaches are the most effective for managing a specific complexity problem.

Generally, the approaches can be divided in 4 categories according to their focus: Product, product portfolio, process and organization (Gießmann, 2010, pp. 57-70). The most important single approaches, focused on product, are modular concept, modular system, standardization, using same parts, platform concept, differential construction and intergral construction. In the category product portfolio, the approaches packaging, reducing product range and reducing of customers are referred in literature. The third category comprises the single approaches postponement concept, standardization of processes and modularity of processes and are focused on process. Further, in the category organization, the approaches delayering and empowerment are pointed out.

In scientific literature, several objectives and strategies for complexity management and approaches' application exist: Complexity reduction, mastering, avoidance, outsourcing and increasing, as well as the acceptance of company's complexity. The strategies have different focuses and time frames.

Complexity reduction is focused on a direct and short-term reduction of parts, products and processes (Wildemann, 2013, pp. 76-77). Mastering of complexity is characterized by effectively handling unavoidable complexity along the value chain and has a medium-term to long-term focus (Wildemann, 2005, p. 36; Wildemann, 2013, pp. 76, 78). The strategy with the longest time horizon is the strategy complexity avoidance. Its objective is to avoid and prevent the generation of complexity in an early stage (Wildemann, 2013, pp. 76, 79). A further strategy is the idea of complexity outsourcing. The aim is to displace complexity to an external business partner to reduce company's internal complexity, costs and risks (Rosenberg, 2002, p. 192; Schönsleben, 2011, p. 72, Gabath, 2008, p. 67). In contrast to the strategy complexity reduction, the target-oriented increasing of complexity is also referred to in scientific literature (Meyer, 2007, p. 35; Puhl, 1999, p. 23; Kirchhof, 2003, pp. 62-63). However, the complexity strategies outsourcing and increasing have less relevance in literature and practice (Schoeneberg, 2014a, p. 21; Meyer, 2007, p. 35). The same can be seen for the strategy complexity acceptance, which is also referred to in literature (Hasenpusch, Moos and Schwellbach, 2004, p. 137).

Based on literature, the mentioned single approaches for managing and optimizing company's complexity are applied for 6 different purposes: Complexity reduction, mastering, avoidance, outsourcing and increasing, as well as general for complexity management. Generally, the different approaches are focused on more than one purpose. The main important strategies for single approaches' application are complexity reduction, mastering and avoidance (Wildemann, 2012, p. 69; Lasch and Gießmann, 2009a, p. 198; Schuh and Schwenk, 2001, pp. 32-40; Kaiser, 1995, p. 102).

In literature, further objectives are described for managing complexity. According to Krause, Franke and Gausemeier (2007, pp. 15-16), complexity identification, complexity evaluation and the determination of the optimum complexity degree are also important objectives for complexity management and to improve transparency. Dehnen (2004, p. 99) argues further that complexity management's objective is to concentrate the available resources in an optimum way regarding company's strengths and weaknesses and market's opportunities and risks.

Complexity management requires approaches for complexity's understanding, simplification, transformation and evaluation (Hünerberg and Mann, 2009, p. 3). For company's success, it is necessary to implement a complexity management in company's management process as an integrated concept (Kersten, 2011, pp. 17-18). A successful complexity management approach enables a balance between external market's complexity and internal company's complexity (Rosemann, 1998, p. 61; Kaiser, 1995, p. 17). In literature, several requirements for a complexity management approach exist. According to Lasch and Gießmann (2009a, pp. 203-206), 11 main requirements were defined and clustered to 3 main categories:

- Structural: Recurring cycle, modular structure.
- Functional: Practicability and transparency, identifying the complexity problem, methods for complexity management, application of key figures, approach for capability planning.
- Cause related: Identifying complexity drivers, identifying complexity driver's interdependencies, evaluation of complexity drivers and evaluation of complexity (degree).

Previous approaches for complexity management are focused on different targets and fields in a company and along the value chain and consist of the following stages: Complexity analysis, complexity evaluation, determination of complexity strategies and instruments, complexity planning, implementation of a complexity management in the company and/or department, as well as complexity controlling.

As already mentioned, complexity management is a strategic issue to be competitive. Managing a company's complexity requires an optimum fit between internal and external complexity. These comprise all parts of the value chain, especially the field product development. Based on literature, product development has the biggest influence on company's complexity and the increasing costs along the value chain. Thus, it is necessary to develop and implement a complexity management approach in this field (see chapter 6). The following subsection 2.1.2 presents the basics of the issue product development and its complexity.

2.1.2 Product development

During the last years, manufacturing companies are confronted with technology innovations, dynamic environmental conditions, changing customer requirements, market's globalization and market uncertainty, which often lead to an increase of complexity (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Perona and Miragliotta, 2004, p. 103; Gerschberger *et al.*, 2012, p. 1016). Further, the manufacturers are forced to ensure the environmental compatibility of their products by developing new innovations (Ruppert, 2007, p. 80). As a result of this, the companies are forced to bring innovative products in higher quality to the market more frequently (Ragatz, Handfield and Petersen, 2002, p. 389). In addition, more and more country and technological specific parts and products have to be developed and produced (Klug, 2010, p. 41). According to Schaefer (1999, p. 311) and Chapman and Hyland (2004, p. 553), product development and innovation is an important key factor for business' success. Today, modern products are often complex products, because they consist of "thousands of parts and take hundreds of manufacturing and assembly steps to be produced" (ElMaraghy *et al.*, 2012, p. 793). Further, complex products comprise mechanical and electrical components, as well as software, control modules and human-machine interfaces (ElMaraghy *et al.*, 2012, p. 793). For product's success, it is important that the product fulfills all customer's requirements so that customers are willing to buy it (Ponn and Lindemann, 2008, p. 273). Thus, product development is an important source for companies to be competitive and to gain a competitive advantage over other business firms (Schaefer, 1999, p. 311). In addition, product development becomes a central importance for company's strategy (Clark and Fujimoto, 1991, pp. 1-15; Davila, 2000, p. 383; Gupta and Wilemon, 1990, p. 24). According to Ragatz, Handfield and Petersen (2002, p. 390), product development is the core process for a new global economy's success.

Product development is one of the most complex and nontransparent tasks and uncertain processes in the company (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386; Specht and Beckmann, 1996, pp. 25-26). It has the biggest influence on a company's complexity (Krause, Franke and Gausemeier, 2007, pp. 3-15). During the development process, information, material and energy are converted (Schlick, Kausch and Tackenberg, 2008, p. 95). Product development's objective is "to translate an idea into a tangible physical asset" (Davila, 2000, p. 385). Krishnan and Ulrich (2001, p. 1) define product development as the "transformation of a market opportunity and a set of assumptions about product technology into a product available for sale".

Complexity in product development has continuously increased over the last years (Lübke, 2007, pp. 1-4; Krause, Franke and Gausemeier, 2007, pp. 3-4; ElMaraghy *et al.*, 2012, pp. 793-797). Product development's complexity comes from a variety of internal and external sources, called complexity drivers (Dehnen, 2004, pp. 32-35). For example, the internal sources comprise the products, the processes and the technologies. The market with its trends, competitors, customer requirements and restrictions by law belong to the external sources (Ophey, 2005, p. 19). Other reasons for increasing complexity in product development are the increasing number of product launches in the market, shorter product lifecycles and customer's demands for new and innovative products (Caridi, Pero and Sianesi, 2009, p. 381). Increasing complexity, especially in product development, leads to increasing costs in all parts along the value chain (Schulte, 1992, pp. 86-87). For manufacturing companies, managing company's complexity is a strategic issue to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). Thus, product development's relevance has changed significantly over the last years and became a central importance in a company's strategy (Davila, 2000, p. 383).

Product development is mainly characterized by 3 categories: Product, product portfolio and product development process (Tomiyama and D'Amelio, 2007, p. 473; Vogel and Lasch, 2015, p. 101). Based on these categories, the following 3 complexity drivers are derived:

- **Product complexity:**
  It is characterized by its product design, the number of parts, elements or materials and their interdependencies, as well as the rate at which new products are introduced or existing products are changed (Edersheim and Wilson, 1992, pp. 27-33; Kirchhof, 2003, p. 40). Further reasons for increasing product's complexity are the rapid technological development and the fact that products have become "significantly multi-disciplinary or even inter-disciplinary" (Tomiyama and D'Amelio, 2007, p. 473). Regarding product complexity's measurement, ElMaraghy and ElMaraghy (2014, p. 5) argue that product complexity can be measured based on variety.

- **Process complexity:**
  Process complexity is mainly characterized by 3 parameters: The amount of different development tasks and their interdependencies (Lenders, 2009, p. 17), the process design and dynamics, as well as the multidimensional target expectation (Edersheim and Wilson, 1992, pp. 28-34; Klabunde, 2003, p. 8; Kirchhof, 2003, p. 40). Process design comprises the number of direct and indirect process steps, their interdependencies, the design of process interfaces, the level of difficulty, as well as the controllability and consistency of each step. Process dynamics refer to the rate at which processes or product designs and operational parameters, for example tolerances, are changing (Edersheim and Wilson, 1992, pp. 28-34; Klabunde, 2003, p. 8; Kirchhof, 2003, p. 40). Furthermore, process complexity describes the multi-dimensional demand for a structural coordination between different interfaces (Dehnen, 2004, p. 34) and can be attributed to the stakeholders' involvement in the product development process. During the development process, more and more stakeholders are involved and their roles are often changing. This leads to an increase in process complexity (Tomiyama and D'Amelio, 2007, p. 473).

- **Product portfolio complexity:**
  It is determined by the product or variant range, the number of their elements and the dynamics of product portfolio's variability (Kirchhof, 2003, p. 40; Lübke, 2007, p. 173; Schoeller, 2009, p. 50). The product range is described by the amount of different product types (e.g. cars, trucks, etc.). Product's variant range comprises the amount of different product variants (e.g. limousine, SUV, etc.) (Renner, 2007, p. 12).

As already mentioned, complexity drivers are factors or indicators, which influence a system's complexity. Complexity drivers play a significant role for complexity management. They describe the complexity in a system and help to evaluate and handle it (Vogel and Lasch, 2016, p. 2). As a result of this, managing and controlling product development's complexity requires a detailed complexity analysis and understanding in the already mentioned 3 categories (Dehnen, 2004, p. 9; ElMaraghy *et al.*, 2012, p. 798). Beyond these categories, Ponn and Lindemann (2008, p. 7) argue that the applied methods and instruments in product development are also important aspects. ElMaraghy *et al.* (2012, p. 798) describe further that the development of methodologies and metrics for sustainable competitiveness is also important for managing product development's complexity.

A further important factor for company's success is the time for product development (Murmann, 1994, p. 237). In the last years, the development time of industrial products has been reduced strongly. Reasons are customer's behavior change, hardly predictable market fluctuations and increasing globalization. As a consequence of this, product development processes have to be adjusted often and quickly to the changed boundary conditions (Krause, Franke and Gausemeier, 2007, p. 89). Product development process is often the longest part of bringing a product to market (Govil and Proth, 2002, p. 103) and is characterized by uncertainty, which results from the ambiguity about target's achievement (Lenders, 2009, p. 17). That includes uncertainties in time (e.g. target achievement at the planned date), resources (e.g. required financial or personnel resources), market (e.g. information about market's or customer's requirements), technology (e.g. knowledge about technology) and organization (e.g. project team or company's higher management) (Lenders, 2009, p. 17; Thiebes and Plankert, 2014, pp. 167-168; Dehnen, 2004, pp. 37-38; Herstatt, Buse and Napp, 2007, p. 11).

During the product development process, 80% of product's and development's costs (Bayer, 2010, p. 89) and the corresponding processes for production and procurement are determined (Dehnen, 2004, p. 26; Lübke, 2007, pp. 70-71; Bick and Drexl-Wittbecker, 2008, pp. 70-71). Product development's costs are influenced by the variety of the different development tasks and all expenditures regarding the development project, for example the required resources and working materials (Zich, 1996, p. 10; Dellanoi, 2006, p. 56). The costs gain more and more importance, because the increase of variants in the product portfolio results in a reduction of the sold amount per developed product variant (Dellanoi, 2006, p. 56). Therefore, an exact definition of market's and customer's demands regarding the product is essential (Kairies, 2006, p. 104).

In principle, the product development process is structured in different phases. Each phase is based on the results of the previous development phase (Bick and Drexl-Wittbecker, 2008, p. 69). According to Dehnen (2004, pp. 23-26) and Davila (2000, p. 385), the product development process can be structured in the following 5 phases:

- **Planning phase**

  Product development starts with the planning phase and the product idea. The objective of the first phase is to concretize the requirements and the development project. The product characteristics, the target markets and the product portfolio are defined based on customer requirements, economic market changes, technological trends and the competitors. Furthermore, the availability of the required resources is checked. At the end of the planning phase, the qualitative targets (e.g. product's characteristics, milestones, etc.) are transferred to the product specification book.

- **Concept phase**

  In the second phase, the requirements of the product specification book are concretized more in detail. Furthermore, product's concept is specified based on the product architecture. During the concept phase, different product architectures are defined based on the product specification book. At the end of the concept phase, the specific targets (e.g. costs, time and quality) are transferred to the functional specification book.

- **Product and process realization phase**

  The objective is to realize the presettings of the functional specification book. During the third phase, the physical products, including the particular parts, components and modules, are developed and the corresponding processes for production and procurement are determined based on the functional specification book.

- **Testing**

  In the fourth phase, the developed parts, components and modules, as well as the corresponding processes are tested and compared with the functional specification book. The objective is to confirm that the product fulfills all requirements and is prepared for its release. If the presettings are not fulfilled, the product and process realization phase is passed through again and product's concept or specifications are reevaluated.

- **Production start-up**

  During the last phase, test and pilot series are used to check the adherence of time, quality and cost targets before starting the serial production. Potential failures and disturbances have to be identified and eliminated. At the end of this phase, the product release and the start of production (SoP) occur.

At the beginning of the product development process, project's targets and costs, as well as the amount of required resources are defined. Furthermore, the availability of the required resources is checked. The amount of required resources is directly connected with the amount of product variants and processes. For a development project's success, it is fundamental to use the available resources efficiently, because resource's amount is limited. Thus, resource planning during the development process is needed. The following subsection 2.1.3 is concerned with the issue resource planning and describes its importance and necessity for the company.

2.1.3 Resource planning

At the present time, companies in high-technology marketplaces are confronted with technology innovations, dynamic market environment, market's globalization, increasing number of demanding customers and uncertainty (Voigt *et al.*, 2011, p. 1; Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Perona and Miragliotta, 2004, p. 103). As already mentioned, for company's success, it is fundamental to bring new products quickly and with customer's individual settings to the market. In consequence, the companies cope with these trends by developing new product variants, which lead to an increased complexity in the company (Brosch and Krause, 2011, p. 1) and especially in product development (Kim and Wilemon, 2012, p. 1). For developing new product variants, resources are required (Wleklinski, 2001, p. 27, Bohne, 1998, pp. 9-10; Zich, 1996, p. 11).

In product development and other parts along the value chain, the amount of required resources is associated with the variety of products and processes (Bohne, 1998, pp. 9-10; Franke and Firchau, 2001, p. 9) and product development's complexity (Bohne, 1998, pp. 9-10). Product's and process' variety are complexity drivers, which have to be managed. According to Collinson and Jay (2012, p. 33), complexity wastes resources, because things are done, which are not value adding. Thus, resources and their planning become a central role for product development and company's success (Vogel, 2017, pp. 84, 92).

Resource planning comprises the quantitative planning of human, material and financial resources over time within a project. The employees within a development project use resources for their development work. For resource planning, the planning phase within the development process becomes a central importance, because the product portfolio is specified there and the availability of the required resources is checked. The success of a development project is closely connected to the amount of available resources. In successful development projects, the required resources are available in a higher proportion than in less successful projects. However, the qualitative and quantitative amount of the resources is restricted. Thus, resources play a significant role for product development's effort and have to be applied efficiently. In the case of resource's shortage, company's departments have to use the available resources together. Thereby, it is necessary to find an optimum way for resources' division.

As already mentioned, resources are required for developing new product variants (Wleklinski, 2001, p. 27, Bohne, 1998, pp. 9-10; Zich, 1996, p. 11). In literature, the term "resource" is described as what is available in the company and directly or indirectly accessible (Müller-Stewens and Lechner, 2003, p. 357). Resources can be differentiaded in 'material/tangible resources' (physical available resources, e.g. equipment, facilities, machineries or capital assets), 'immaterial/intangible resources' (not physically available resources, e.g. know-how, intelligence, brands, image or patents) and 'human resources' (Stirzel, 2010, p. 119; Bullinger, Fähnrich and Meiren, 2003, p. 278; Dehnen, 2004, pp. 84-85). Furthermore, the resources can be classified according to their origin in 'internal resources' and 'external resources' (Stirzel, 2010, p. 119) and according to their property in 'consumable resources' (e.g. energy, raw materials or tools) and 'producible resources' (e.g. products or final goods) (Schönsleben, 2011, p. 414).

As already mentioned, complexity management and resource planning are fundamental for company's success. In today's highly competitive environment, the companies are forced to develop and bring new and innovative products quickly and with customer's individual settings to the market. During the development process, the product portfolio and 80% of product's costs are defined. Furthermore, the structure and characteristics of the different products, the development time, the amount of required resources, as well as the corresponding processes for production and procurement are determined. The amount of required resources and the development costs are connected directly to the development time, as well as product's and process' variety and complexity. Generally, increasing complexity leads to increasing costs in all parts along the value chain. Thus, it is necessary to implement a complexity management approach in combination with an efficient and target-oriented resource planning in the company and especially in variant-rich product development to be competitive.

2.2 Gaps in scientific literature

In this work, the literature search resulted in a certain amount of literature sources, but only a few are relevant. As a result of literature's analysis, several research gaps were identified. The purpose of this dissertation is to close the research gaps with implications for further research. The results of the literature research regarding the different issues and their research gaps are presented as follows:

- **Complexity drivers in manufacturing companies and along the value chain:**

  Search result: **11,425** identified literature sources ➔ **235** relevant sources

  The identified literature sources were analyzed and synthesized to identify existing literature reviews and studies. Previous literature studies about complexity drivers have been done by 4 authors. They cover complexity drivers only in specific fields, such as logistics, supply chains and general in manufacturing companies and comprise a restricted time period of 20 years (1991-2011). However, the research methodology, including research questions, databases, search terms and synthesizing methods, are not described by the authors. Furthermore, a comparison between their findings and the findings of other literature sources was not provided by all authors. These issues are essential to determine the current state of knowledge about a particular research topic in a literature review. So, they do not fulfill the requirements of a literature review in general. Besides the methodical gaps, a more general overview about complexity drivers in manufacturing companies and along the total value chain without a time-restriction does not exist yet. In addition, no comparison and discussion about existing definitions, an overall definition and classification system for complexity drivers, as well as an overview about specific approaches for complexity driver's identification, operationalization and visualization are presented in the previous literature studies. This gap will be closed by presenting a systematic, explicit and reproducible literature review (see chapter 3).

- **Single approaches for managing complexity and their targeted strategies:**

  Search result: **130,722** identified literature sources ➔ **288** relevant sources

  The researched literature was analyzed and synthesized regarding specific single approaches for managing complexity and their targeted strategy. The synthesizing process resulted in 288 relevant literature sources in the time period between 1962 and 2015. In scientific literature, a vast number of different single approaches for managing complexity in the company and along the value chain is described. Further, the single approaches are focused on specific strategies or objectives. However, a general overview about the different single approaches and their focus and targeted strategies, including a comparison between the different results and literature sources, does not exist yet. This gap will also be closed by presenting a detailed literature review (see subsection 5.2.2).

- **Previous empirical studies in the field complexity management:**

  Search result: **26,699** identified literature sources ➔ **72** relevant empirical studies

  Before starting a new empirical research, it is important to review existing empirical studies in the same or a similar scientific area to get an overview about their objectives, research methodologies and findings (Madu, 1998, pp. 354-355). The objective of the third literature research was to identify first all existing empirical researches concerning complexity management in manufacturing companies and especially in product development. A further objective was to identify all previous studies, which contain the issues 'complexity drivers and their effects on company's complexity' and 'application of specific single approaches for complexity management and their targeted strategy' during the last years. As a result of literature's analysis, 72 empirical studies regarding complexity management in various industry branches and regions/countries already exist (see subsection 4.2.3 and Table 15). The previous studies are focused on different fields in the company and along the value chain and were conducted in the time period between 1999 and 2015. The studies were analyzed and synthesized regarding their content, research objectives, focus, field of industry, region/country, research period and applied data collection methodology. Most of the empirical studies are focused on the fields general in manufacturing companies (N: 32) and internal supply chain (N: 16). Regarding the field product development, only 6 empirical studies were performed with different objectives between the time period 2005 and 2013. Furthermore, 13 different studies are focused on complexity drivers. However, an empirical study in the field product development in manufacturing companies in Germany and with focus on complexity drivers, including the identification and analysis of complexity drivers and their effects on company's complexity, as well as a comparison between literature and practice, does not exist yet. Regarding the practical application of specific single approaches for managing complexity and their targeted startegy, literature's analysis showed that an empirical research focused on this issue is missing so far. These gaps will be closed by presenting a systematic, explicit and reproducible empirical research (see chapters 4 and 5).

- **Approach(es) for complexity management, including resource planning:**

  Search result: **13,085** identified literature sources ➔ **48** relevant sources

  In the first step before developing a new complexity management approach, existing literature must be identified, analyzed and evaluated. Furthermore, an overview about the existing complexity management approaches, including their focus, structure, target and applicability for resource planning, has to be described. In the second step, the new approach is developed based on literature's findings. The literature search resulted in 47 relevant approaches in the time period between 1992 and 2014. More than 50% of the existing approaches are focused on general in manufacturing companies. Only 3 approaches are focused on product development. The identified approaches were analyzed and described according to their structure and targets. Further, they were evaluated based on several requirements, which are necessary for a general complexity management approach and a complexity management approach for resource planning, to identify strengths, weaknesses and deficits. As a result of the analyzing and evaluation process, a general approach for variant-rich product development, which consists of all stages and categories and fulfills all requirements, does not exist yet and has to be developed. Regarding the issue resource planning, the previous exsting approaches are analyzed and evaluated based on their applicability for resource planning. This includes the complexity management's objectives, product development's characteristics and objectives, as well as the principle for resource planning and the applicability in product development. The analysis and evaluation process showed that the new general approach for complexiy management, which was developed based on the aforementioned research gap, fulfills all requirements. However, the order of the different stages was not feasible in practice. Therefore, a new and structurally optimized complexity management approach for resource planning, especially in variant-rich product development, is needed to increase particability in practice. Within this thesis, the research gaps are closed by developing a general complexity management approach for variant-rich product development and a complexity management approach, especially for resource planning (see chapters 6 and 7).

In the following chapters 3 to 7, the aforementioned research gaps are closed by using an extended literature research on the different issues as well as an empirical study regarding product development's complexity in the German manufacturing industry. The results from literature are compared with the empirical findings to identify commonalities and differences. In the last chapter 8, the results are summarized (section 8.1) and gaps for future research are pointed out (section 8.2).

3 Complexity drivers in manufacturing companies: A literature review

3.1 Introduction

Technology innovations, dynamic environmental conditions, changing customer requirements, market's globalization and market uncertainty are trends that manufacturing companies cannot escape and that often lead to an increase of complexity (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Perona and Miragliotta, 2004, p. 103; Gerschberger *et al.*, 2012, p. 1016). Within the last decades, complexity has increased continuously in many industries (Schuh, Arnoscht and Rudolf, 2010, p. 1928). This is one of the biggest challenges that manufacturing companies have to face today (ElMaraghy *et al.*, 2012, p. 793). The reasons are internal and external sources of complexity, so called complexity drivers.

The origin of the term complexity comes from the Latin word "complexus", which means "extensive, interrelated, confusing, entwined or twisted together" (Pfeifer *et al.*, 1989, p. 889; ElMaraghy *et al.*, 2012, p. 794). This is similar to the Oxford Dictionaries (2014) definition of "complex": Something is complex if it is "consisting of many different and connected parts" and it is "not easy to analyze or understand". Complexity is directly connected with a system and its terminology (Ulrich, 1970, pp. 115-117; Hoffmann, 2000, p. 37; Prillmann, 1996, pp. 57-58). In literature, complexity is defined as a part of system's property (Lammers, 2012, pp. 16-19). Gell-Mann (1994, p. 68) and Luhmann (1980, p. 1064) argue that the definition of complexity always needs a description of system's level of detail. The approaches of the system theory provide an opportunity to divide a system in several subsystems and support the determination of system's level of detail (Skirde, 2015, pp. 10-17). The system theory can be attributed to the natural science, whereby control und adjustment operations are considered in a system's context (Bertalanffy, 1950). For the term system, several definitions exist in literature. Göpfert (2009, p. 14) defines a system as a unit, consisting of several parts. Ulrich (1970, p. 105) and Patzak (1982, p. 19) extend this definition and describe a system as an entity of elements, which are related to each other or where a concrete relation can be made through the elements. Ulrich (1970, pp. 115-117) argues that the elements and their relations are significant for system's complexity and in dynamic systems, the system can suppose a high amount of different conditions. Thus, complexity would be described by an amount of variables or elements (Grübner, 2007, pp. 77-78).

In principle, a system is ever surrounded by an environment and can be isolated by the system boundary (Skirde, 2015, p. 10). However, the system and its complexity are influenced by the environment (Ulrich, 1970, pp. 105-107, 112).

Complexity and systems are consisting of the interaction between elements and relations (Bertalanffy, 1950, p. 143; Luhmann, 1980, p. 1064). Thereby, the elements are representing the tangible parts of a system, whereas the connection between the elements is described by relations (Skirde, 2015, p. 12). Consequently, a system's complexity depends on the amount of existing parts or components, the connections between them and the diversity of these relations and elements (Luhmann, 1980, pp. 1064-1065; ElMaraghy *et al.*, 2012, pp. 794-795).

In this context, Patzak (1982, pp. 21-23) and Meyer (2007, p. 26) describe elements' diversity as variety and relations' diversity as connectivity. Bronner (1992, p. 1122) extends this definition by consideration of system's dynamic and comprises the variation of system's behavior over time.

Complexity has been discussed in several fields of research, such as physics, biology, chemistry, mathematics, computer science, economics, engineering and management, as well as philosophy (Isik, 2010, p. 3682; Bozarth *et al.*, 2009, p. 79). Thus, in scientific literature, there are many different definitions for the term "complexity", because the meaning is vague and ambiguous. There is no explicit, universal and widely accepted definition (Riedl, 2000, pp. 3-7; Brosch and Krause, 2011, p. 2; ElMaraghy *et al.*, 2012, p. 794). As a result, the term "complexity" is often used synonymously with the term "complicated" (Gießmann, 2010, p. 30). Meijer (2006, p. 1) argues that "complexity is in the eye of the beholder". Complexity is driven by the sensation or perspective of an individual. What is complex to someone, might not be complex to another (Leeuw, Grotenhuis and Goor, 2013, p. 961; Grübner, 2007, p. 41).

There are 2 types of complexity: Good and bad. The good type of complexity is necessary. It helps a company to gain market shares and is value adding. On the other side, bad complexity brings little value, reduces revenue and causes excessive costs (ElMaraghy *et al.*, 2012, p. 811; Isik, 2010, p. 3681). Colwell (2005, pp. 10-12) defines 32 types of complexity in 12 different areas and disciplines, such as structural, functional, technical, computational and operational complexity. Götzfried (2013, pp. 14-16) describes 17 definitions of complexity in 4 different research fields, such as systems theory, organizational theory, product design and operations management. In literature, increasing complexity is often related to increasing costs (Meyer, 2007, p. 1). Managing a system's complexity requires an optimum fit between internal and external complexity (Schuh, 2005, pp. 34-35; Vogel and Lasch, 2015, p. 100). The complexity management comprises the application of the mentioned complexity consideration with the aim of a target-oriented complexity design (Meyer, 2007, p. 25). Schuh (2005, pp. 34-35) argues further that complexity management comprises 4 tasks: Designing the necessary variety, handling variety-increasing factors, reducing variety and controlling complex systems (Vogel and Lasch, 2015, p. 100).

Generally, complexity is caused by internal and external factors (Meyer, 2007, pp. 26-29). Meyer (2007, p. 26) defines these factors as complexity drivers. According to the Business Dictionary (2014), a driver causes a condition or decision or has an effect on elements or a system. Complexity drivers lead to an increased level of complexity in comparison to an initial situation (Meyer, 2007, p. 26). Furthermore, complexity drivers can cause turbulences and new functional models in a system (Krizanits, 2015, p. 44).

For complexity's operationalization, Schuh (2005, p. 8) argues that it can only be realized by several complexity factors, which interact with each other.

Identifying, analyzing and understanding complexity drivers as main elements related to complexity are the first steps to develop and implement a clear strategy to handle complexity (Miragliotta, Perona and Portioli-Staudacher, 2002, pp. 384-388; Serdarasan, 2011, p. 792). Without an idea of complexity drivers, it would be difficult to develop an effective complexity strategy (Serdarasan, 2011, p. 792). Heydari and Dalili (2012, p. 64) argue that a research in complexity management needs to know, what the key drivers of complexity in a system are. The management of complexity is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383; Schuh, 2005, p. 13; Budde and Golovatchev, 2011, p. 2). In the study “Managing Complexity in Automotive Engineering”, Erkayhan (2011, p. 2) concludes that the complexity drivers are the main adjusting levers for improvements of the company’s success. Thus, complexity drivers play a significant role for complexity management, because they describe a system’s complexity and help to evaluate and handle it.

Previous literature studies about complexity drivers have been done by Meyer (2007, pp. 182-183), Serdarasan (2011, pp. 793-795; 2013, pp. 534-535) and Wildemann and Voigt (2011, pp. 44-52, 63-72) and comprise a time period of 20 years (1991-2011). They cover complexity drivers on specific issues, such as logistics, supply chains and general in manufacturing companies. In total, 99 literature sources, such as articles, books and PhD theses in the research period between 1991 and 2011, form their research. Furthermore, 281 complexity drivers are identified in total. Although, these literature studies cover a lot of literature sources and complexity drivers in the referred fields, a systematic, explicit and reproducible method for identification, evaluation and synthesizing the existing literature about complexity drivers is not described (Fink, 2014, p. 3). For example, the authors in the previous literature studies have not described specific research questions, databases, search terms and synthesizing methods. In addition, not all authors provide a comparison between their findings and the findings of other literature sources. However, these are essential to determine the current state of knowledge about a particular research issue in a literature review. So, they do not fulfill the requirements of a literature review in general.

This chapter’s purpose is a literature review of complexity drivers in manufacturing companies and along the value chain, including the fields product development, procurement/purchasing, logistics, production, order processing/distribution/sale, internal supply chain and remanufacturing, which fulfills the mentioned requirements.

The contribution of this review is to develop additional knowledge for science and practice by describing, what is currently known on the issue of complexity drivers. From scientific perspective, this literature review presents a current state of the art about complexity drivers and gives the researcher a first insight and general understanding about complexity drivers before starting a research project in this field. It closes a currently existing gap in scientific literature. The literature review can be used for a dissertation or research proposal to give an overview about the issue of complexity drivers and is helpful for researchers, who have no prior knowledge in this field. Further, it helps the researcher to avoid time-wasting and research effort by “reinventing the wheel”. Within this research, the gaps for future research are pointed out. Based on this review, researchers can build new ideas and theories for their own research. The research methodology, including research questions, databases and synthesizing methods are described in detail to increase transparency. This enables the researcher to reproduce the findings. The literature review provides a comprehensive survey of significant literature (e.g. academic journal articles, books, essays, PhD theses, conference proceedings, etc.) and their results based on analyzing, synthesizing and summarizing the existing literature. Furthermore, the different literature sources and the trends of complexity drivers in literature and in the different fields (general in manufacturing companies and/or along the value chain) over the last 25 years are described. The trends show the researcher how essential the topic complexity drivers is in literature and that it is thus interesting for future research. However, interesting topics for academic people do not have to be important for practice. To avoid this trade off, we also include the practical perspective in our point of view. In addition, different definitions of complexity drivers are analyzed and described. A new overall definition of complexity drivers is presented. Furthermore, the existing approaches for complexity driver's identification, operationalization and visualization are identified and specified according to their focus. The identified complexity drivers are clustered in aggregated complexity driver's main categories according to their characteristics to provide a general classification system without overlaps. From practical perspective, this literature review gives the practitioner a first insight and understanding about the phenomena of complexity drivers and their importance. In several empirical studies, for example from Wildemann and Voigt (2011, pp. 113-170), Gießmann (2010, pp. 87-117) and Gießmann and Lasch (2010, pp. 152-156), the issue complexity in companies and its drivers were analyzed. The result was that companies are aware of complexity and some of its causes, but they often do not know, how to handle it, because of a lack of specific methods or tools for complexity driver's identification, operationalization or visualization. This study answers the following manager's questions "What are complexity drivers?", "Why they are so important for me?" and "How can I identify, operationalize and visualize complexity drivers?" by providing an overall definition about complexity drivers and an overview about the existing approaches for complexity driver's identification, operationalization and visualization. Beyond, the practitioners get an overall selection of different approaches and their focuses and can choose the right one for solving their task or problem. Furthermore, a list of theoretical existing complexity drivers, which were found in literature, are described, so the management has a general overview about complexity drivers and can compare these findings with their own complexity drivers to identify commonalities and differences, as well as get a first indication. This review collects existing approaches for complexity driver's identification, operationalization and visualization based on literature. Therefore, it can be used as a basis to gain first implications about complexity drivers, their identification, operationalization and visualization. Further research will be needed to create helpful advice for practitioners to detect complexity issues, as well as to present methodological support to detect causes of complexity and their effects.

This literature review is structured as follows: In section 3.2, an overview about the research method is given. Some definitions of literature reviews are disclosed and a framework for constructing a literature review is specified. Section 3.3 presents the literature review about complexity drivers with an overview about different definitions and approaches for identification, operationalization and visualization. The most discussed complexity drivers in manufacturing companies and along the value chain are described. Section 3.4 concludes this research and closes the research gap with implication for future research.

3.2 Research method

3.2.1 Research methodology and boundary definition

The aim of this study is a systematic, explicit and reproducible literature review about complexity drivers in manufacturing companies and along the value chain, which provides definitions of complexity drivers and existing approaches for complexity driver's identification, operationalization and visualization. The existing literature was identified, evaluated and synthesized by using qualitative data analysis techniques to point out the existing literature sources and their focuses, as well as the trends and issues. The literature results are compared with each other. To provide a comprehensive literature review, we used the methodology of Fink (2014, pp. 3-5) and structured this chapter accordingly. Literature reviews have been used for many years in scientific research and scholar findings. They are a long-standing tradition, but the definitions are tight (Bruce, 1994, pp. 217-218). Fink (2014, p. 3) defines a literature review as a "systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners". Brewerton and Millward (2001, pp. 36-40) describe a literature review as a content analysis that uses qualitative and quantitative techniques to find structural and content criteria. According to Meredith (1993, cited in Jain and Singh, 2014, p. 788), a literature review is a "summary of the existing literature by finding research focus, trends, and issues". Within this research, we follow the definitions of Fink (2014, p. 3), Brewerton and Millward (2001, pp. 36-40) and Meredith (1993).

Fink (2014, pp. 3-4) divides a literature review into 7 tasks. The first step is selecting the research questions. Research questions are precisely stated questions, which guide the literature review. The next step is to select the required sources, such as bibliographic or article databases, Web sites and other sources to determine relevant literature. Before starting the literature review, the researcher has to define the search terms. To review the databases and search terms, the researcher should ask experts or other researchers. The next steps are applying practical and methodological screening criteria to identify and select the relevant literature from the entity of found literature. To reject irrelevant articles, the researcher has to screen the literature by setting practical and methodological criteria.

According to Fink (2014, pp. 3-4), the first step is to define the research questions. The benefit of research questions is that they already contain the words the reviewer needs to search for online to find relevant literature. These words or search terms are called key words, descriptors or identifiers (Fink, 2014, p. 20).

For this literature review, we determined the following research questions including the relevant key word 'complexity driver':

- RQ 1: What are the different definitions of complexity drivers that currently exist in manufacturing companies and along the value chain?
- RQ 2: What methods are applied in literature for complexity driver's identification, operationalization, and visualization?
- RQ 3: What complexity drivers occur in manufacturing companies and along the value chain?

Before conducting a literature research, it is necessary to define the right search terms and databases. The search terms are based on the words that frame the research questions. In literature, several paraphrases for complexity driver exist. These paraphrases are usually a combination of the terms "factor", "indicator", "source", "parameter", "variable", "symptom", "phenomenon", "dimension", "force" and "property" and the term "complexity driver" (see subsection 3.3.2). When comparing the meaning of these different word combinations, it can be seen that the lowest common denominator is complexity driver (see Figure 3). Thus, we limited our literature research to the search term complexity driver.

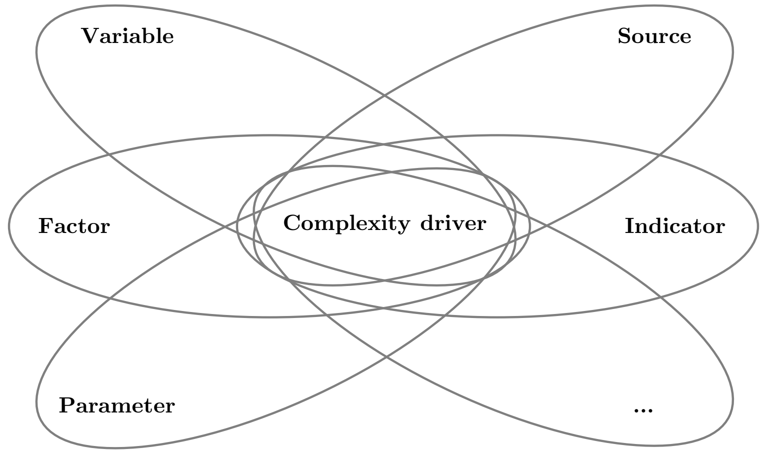


Figure 3: Paraphrases of the term complexity driver and their intersections

A researcher must use a “particular grammar and logic” to conduct a search that will acquire the appropriate publications (Fink, 2014, p. 3). One possibility is to combine the key words and other terms with Boolean operators, such as AND, OR and NOT. Further the operator NEAR can be used to identify literature, where the keywords have a close connection to each other. The application of Boolean operators depends on the specific database. To extend the amount of relevant literature, it is also necessary to search in different languages. In our research, we search in English- and German-language literature. This has 2 reasons: First, English is the global language and applied in the scientific world to provide research findings worldwide. Second, during our literature research we started with English-language sources and found some literature sources with references to German-language sources. This was another reason to extend the research to German-language literature.

According to Saunders, Lewis and Thornhill (2009, pp. 75-78), the finalized search terms are identified through an iterative cycle starting with 1 key word and adding more in the process of research in order to summarize all necessary and possible literature sources and results. Furthermore, the search terms are defined in English and German and then formulated more general to extend the results and to prevent the elimination of important articles. We started our research by using the key words “Komplexitätstreiber” and “complexity driver” and formulated the search term ‘Komplexitätstreiber OR complexity driver‘. After reviewing the found literature, we found out that a lot of sources also used the term “Treiber der Komplexität” or “driver of complexity”, so we added these terms to our first search term and received the new term ‘Komplexitätstreiber OR Treiber der Komplexität OR complexity driver OR driver of complexity’. During the following search process, it became clear that sometimes these keywords are separated by other words so we implemented the NEAR operator to cover all existing and relevant literature. The finalized search terms are described in Table 1.

After defining the right search terms, a researcher must examine all sources systematically by using online bibliographic or article databases. Databases are often specialized in a specific research area. The research was performed in English and German by using the following 8 English and German databases: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink.

The used databases were also defined through an iterative cycle. In our research, we started by using the databases EBSCOhost, JSTOR, GENIOS/WISO and Google Scholar. EBSCOhost and JSTOR are one of the biggest databases for academic research and connected with numerous other databases. During our research process on Google Scholar, some literature sources were found on other specific databases, such as Emerald, IEEE Xplore, ScienceDirect and SpringerLink. Thus, these databases were also included in the research process.

Table 1 shows the general framework of our literature collection including the research focus, applied databases and search terms. Furthermore, the framework contains the results and search dates at an aggregate level to provide first insights. In our research, the time period was restricted between 1900/01/01 – 2015/12/31. The different frameworks with all precise search terms, results and searching dates are shown in the appendix (Table 45).

Table 1: General framework of literature collection

Focus	Database	Search terms	Date	Results
■ General in manufacturing companies	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND ...	April & May '16	401
		('complexity driver*' OR (driver* N3 complexity)) AND ...		
■ Product Development	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ...	April & May '16	44
		("complexity driver" OR "driver of complexity") AND ...		
■ Procurement/ Purchasing	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND ...	April & May '16	1,001
		("complexity driver*" OR (driver* ndj3 complexity)) AND ...		
■ Logistics	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ...	May '16	3,234
		("complexity driver*" OR "driver* of complexity") AND ...		
■ Production	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND ...	May '16	2,203
		(complexity NEAR/3 driver) AND ...		
■ Order Processing/ Distribution/Sale	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND ...	May & June '16	146
		("complexity driver" OR ("driver complexity"~5)) AND ...		
■ Supply Chain	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND ...	May & June '16	1,726
		(complexity W/3 driver*) AND ...		
■ Remanufacturing	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND ...	May & June '16	2,670
		(Complexity NEAR/3 driver*) AND ...		
			Total:	**11,425**

3.2.2 Research segmentation and overview

The search resulted in 11,425 literature sources including research papers from journals, conference proceedings, working papers, books, essays and PhD theses. However, several literature sources are found repeatedly. According to Fink (2014, p. 5), literature research and analysis always accumulate many publications, but only a few are relevant. Consequently, it is necessary to screen and synthesize the results.

In this research, the searched literature was synthesized based on the qualitative content analysis and the aforementioned research questions. The content analysis is used to analyze literature and to identify the occurrences of specified information systematically. Within the qualitative content analysis, the information is extracted, formatted and evaluated to answer the research questions. The most important aspect is the extraction of the information to gain the required information. Extraction means to read the text, to separate the text in different parts and to decide, which of the given text parts contain information that is relevant for the researcher. The relevant information is then assigned to previously defined categories (Gläser and Laudel, 2010, pp. 197-198). In the qualitative content analysis, this assignment is called coding and is induced by a coding unit. The coding unit is a text passage, which is connected to a certain category or content. The assignment to the defined categories is performed by the researcher, called coder (Kuckartz, 2012, pp. 47-48). However, the researcher and his/her understanding and interpretation influences the extraction and text interpretation (Gläser and Laudel, 2010, p. 201; Kuckartz, 2012, pp. 48-49). When the coding process is done by more than one researcher, a common understanding and interpretation is required (Kuckartz, 2012, pp. 48-49). The defined categories are connected with the research questions and are not fixed. During the extraction process, they can be altered and new categories can also be added. As a result of the extraction, a vast amount of data is collected, which can be used for information formatting and evaluation to answer the research questions. For information evaluation, the researcher compares the different literature sources to identify commonalities and differences (Gläser and Laudel, 2010, pp. 201-206, 212-246).

For analyzing and synthesizing the literature in our research, we followed the approach of the qualitative content analysis and defined in the first step 12 categories based on our 3 research questions. The categories were implemented in a synthesis matrix (see Table 2). The synthesis matrix helps the researcher to organize the identified literature sources and their different contents on an issue.

Table 2: Synthesis matrix for literatures' synthesizing

<table>
<tr><th colspan="3" rowspan="2">Categories
(combined with **RQ**)</th><th colspan="5">Identified literature sources with Author's name(s)</th></tr>
<tr><th>Source #1</th><th>Source #2</th><th>Source #3</th><th>...</th><th>Source #n</th></tr>
<tr><td colspan="3">Definition of complexity drivers (**RQ1**)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Methods for complexity driver's ... (**RQ2**)</td><td colspan="2">... identification</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">... operationalization</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">... visualization</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="8">Complexity drivers in manufacturing companies (**RQ3**)</td><td colspan="2">General in manufacturing companies</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="7">Value Chain</td><td>Product Development</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Procurement/Purchasing</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Logistics</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Production</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Order Processing/Distribution/Sale</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Supply Chain</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Remanufacturing</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

In the next step, we started the extraction process by screening the title and abstracts of the identified papers, books, etc. and eliminated sources without focus in manufacturing companies or the value chain. For example, papers focused on financial, insurance or biological issues were eliminated. Furthermore, we excluded all papers that were found multiple times. Within this procedure, the total amount of found literature sources could be reduced significantly.

Then, we started our detailed literature analysis by searching for the key words “complexity driver” or “driver of [...] complexity” and analyzed the content around the key words. The key words were highlighted in the text and we made notes about our first impressions and thoughts. Afterwards, we read all data repeatedly to achieve an overview of the whole content and separated the text in different parts regarding its content. The parts with relevant information about complexity drivers were assigned to the previously defined categories in our synthesis matrix. The assignment of a specific information to a certain category (coding) was induced by the particular text passage (coding unit). Parts without relevant information were ignored. As a result of our extraction process, a vast amount of data from 235 different literature sources was collected in a table to answer our research questions. For information evaluation, we compared the found information in each category to identify commonalities or differences.

The synthesizing process resulted finally in 235 relevant papers. These papers were published in journal articles (68), books (41), essays (41), PhD theses (55), conference proceedings (13), working papers (11), newspapers (4) and websites (2) in the field of complexity drivers in the time period 1991 to 2015 (see Table 3).

Table 3: List of journals, books and papers published during the period 1991 - 2015

Literature source	Time horizon	Number of publications
Journals	1991 – 2015	68
Books	1993 – 2015	41
Essays	1991 – 2015	41
PhD theses	1991 – 2015	55
Conference proceedings	2010 – 2015	13
Working papers	2000 – 2012	11
Newspapers	1994 – 2009	4
Internet (Websites)	2005 – 2014	2
	Total:	235

Before 1991, no relevant literature sources with regard to the issue complexity drivers were found in our research. One reason could be attributed to the development of the scientific research in the field complexity management (Gießmann and Lasch, 2011, pp. 2-4). According to Gießmann and Lasch (2011, pp. 2-4), complexity management’s development process can be separated in 3 steps: Variant management, complexity management in a narrower sense and integrated complexity management (see Figure 4 from Gießmann and Lasch, 2011, p. 4). These steps do not appear strictly in sequence, but also parallel.

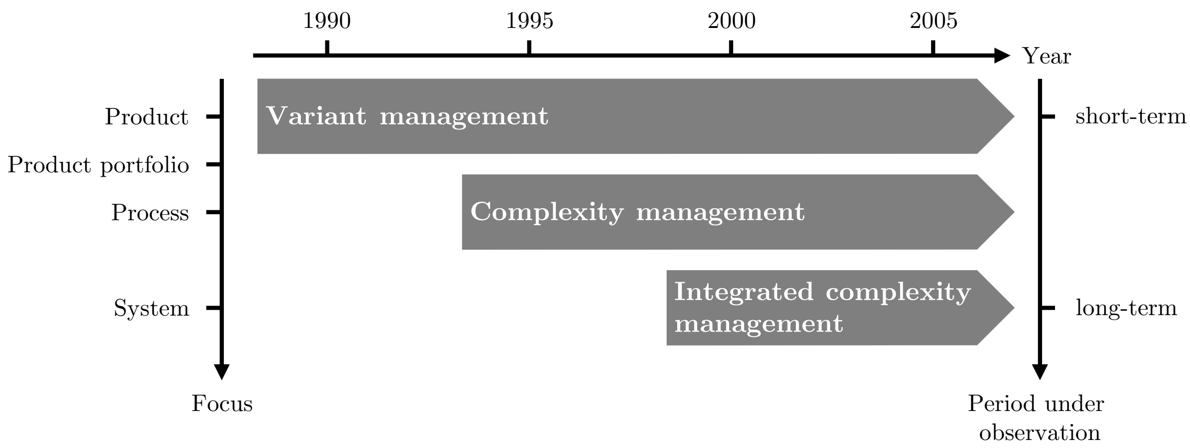


Figure 4: Complexity management's evolution

Due to a change from sellers to buyers market, the companies extend their product portfolio. In consequence, the product portfolio reached a volume that could hardly be managed by the companies (Gießmann and Lasch, 2011, pp. 1-2). Therefore, variant management was developed to handle product's complexity. Variant management's objective is to combine variant's diversity and profitability (Gießmann and Lasch, 2011, p. 2; Franke *et al.*, 2002, pp. 1-12). Product's amount and property was one complexity driver. Within the complexity management, the focus lay more and more upon the processes. Processes were identified as a further complexity driver. In the third step, the upstream and downstream processes and stages were integrated in the focus. Furthermore, the interdependencies between the determining factors, the initiated approaches and company's subsystems were determined. The integrated complexity management provides a concept for an effective handling of complexity problems (Gießmann and Lasch, 2011, pp. 2-4). Therefore, it can be assumed that complexity drivers come more and more into scientific focus at the transition between variant management and complexity management in the early nineties of the last century.

Another reason could be attributed to the definition and understanding of the term "complexity driver". In literature, complexity drivers were defined in many ways (see subsection 3.3.2). For the authors, complexity drivers have an influence on something and are responsible for increasing complexity in a system. In our research, we found out that the first definition of complexity drivers was specified by Schmidt (1992, p. 14) in the year 1992.

In variant management, the sources, which were responsible for increasing variant diversity and complexity, were called "variant drivers" (Schuh, 2005, pp. 34-37). Thus, it is an indication for us that the term "complexity driver" can be attributed to the term "variant driver".

3.3 Literature review about complexity drivers

3.3.1 Overview about literature research results

Table 3 presents an overview about the identified literature sources and the number of publications in the field of complexity drivers in manufacturing companies and along the value chain (published between 1991 and 2015). More than 50% of the publications about complexity drivers were published in journals and PhD theses. Thus, complexity drivers have a high importance in scientific research. Complexity drivers are also mentioned in several books, essays, conference proceedings, as well as working papers with a practical and/or scientific purpose. Working papers are publications from companies or universities with a practical and/or scientific purpose. In this research, most of the identified working papers are practically oriented. Newspapers and the Internet are also literature sources for complexity drivers. After analyzing the different literature sources and their focuses, we conclude that complexity drivers have a high relevance in practice, as well as in scientific research.

As already mentioned, in our research, we identified 235 papers about complexity drivers in literature and clustered them according to their content in 19 clusters (see Table 4). Building the 19 clusters was an iterative process. We started by comparing the papers according to their content and generated the clusters based on their commonalities and differences. 160 papers (68%) are only focused on complexity drivers (Cluster #10), 19 papers (8%) are focused on complexity drivers and complexity driver's definition (Cluster #12) and 12 papers (5%) are focused only on complexity drivers and approaches for complexity driver's identification (Cluster #14). Furthermore, 169 papers (72%) are written in German and 66 (28%) in English.

In addition, we discovered that 212 (90%) of the total amount of 235 papers describe specific complexity drivers in manufacturing companies and along the value chain (Cluster #10 to #19). Regarding publication's language, 154 papers (73%) are written in German and 58 (27%) in English. Furthermore, 23 papers (Cluster #1 to #9) comprise only general information about complexity drivers without the description of specific complexity drivers in manufacturing companies and along the value chain.

Table 4: Paper's classification according to their content

	Content of literature source based on literature's analysis						Results			
		RQ1	RQ2 Approach for...			RQ3				
Paper's classification according to their content	General statement about complexity drivers	Definition of complexity drivers	Complexity driver's identification	Complexity driver's operationalization	Complexity driver's visualization	Overview about complexity drivers	**Total**	%	Number of German literature sources	Number of English literature sources
Cluster #1	•						**4**	1.7%	1	3
Cluster #2	•				•		**1**	0.4%	1	0
Cluster #3		•					**3**	1.3%	1	2
Cluster #4		•	•				**1**	0.4%	1	0
Cluster #5		•	•	•	•		**1**	0.4%	1	0
Cluster #6			•				**8**	3.4%	6	2
Cluster #7			•	•	•		**1**	0.4%	1	0
Cluster #8				•	•		**1**	0.4%	0	1
Cluster #9					•		**3**	1.3%	3	0
Cluster #10						•	**160**	**68.1%**	118	42
Cluster #11	•					•	**2**	0.9%	0	2
Cluster #12		•				•	**19**	**8.1%**	16	3
Cluster #13		•	•			•	**5**	2.1%	2	3
Cluster #14			•			•	**12**	**5.1%**	8	4
Cluster #15			•	•		•	**1**	0.4%	0	1
Cluster #16			•	•	•	•	**7**	3.0%	5	2
Cluster #17				•	•	•	**2**	0.9%	1	1
Cluster #18				•		•	**2**	0.9%	2	0
Cluster #19		•		•	•	•	**2**	0.9%	2	0
Total:	**7**	**31**	**36**	**17**	**18**	**212**	**235**	**100%**	**169**	**66**
Number of German literature sources	2	23	24	12	14	154				
Number of English literature sources	5	8	12	5	4	58				

For separating the literature into the 2 parts 'manufacturing companies' and 'along the value chain', we analyzed the 212 literature sources and the identified complexity drivers regarding their focus. We followed the complexity driver's assignment to certain categories that the paper's authors used. If they describe complexity drivers, which belong to different parts of the value chain, we followed their assignment and used this information in our study. We assumed complexity drivers, which are not assigned to a certain part of the value chain by the authors, to be general in manufacturing companies. This separation is important for the management in a company, because higher management (e.g. CEO or director) needs a vast overview of the whole company and the occurring complexity drivers, whereas managers of certain departments (e.g. senior manager, department manager, team leader) need an overview about complexity drivers in their specific fields of interest.

Previous literature studies about complexity drivers have been done by 4 authors with different objectives: Meyer (2007, pp. 182-183), Serdarasan (2011, pp. 793-795; 2013, pp. 534-535) and Wildemann and Voigt (2011, pp. 44-52, 63-72). Principally, it can be distinguished between literature review and literature overview/survey. A literature overview/survey reviews the existing literature in a particular field of interest on a surface level. However, a literature review analyzes and evaluates the existing literature more in detail as an overview/survey and gives the reader a better understanding of the research (Shah, 2015). Serdarasan (2011, pp. 793-794; 2013, pp. 534-535) signifies her literature studies as reviews and gives a detailed overview of the "literature on supply chain complexity" and its drivers. The literature studies of Meyer (2007, pp. 182-183) and Wildemann and Voigt (2011, pp. 44-52, 63-72) refer to a literature research only on complexity drivers and can be assigned to the category 'literature overview/survey'.

In his PhD thesis, Meyer (2007, pp. 182-183) describes the state of the art regarding specific complexity drivers and their influence on increasing complexity. Before reviewing the literature, Meyer (2007, p. 26) describes his understanding of the term complexity drivers and states that complexity drivers are factors, which influence the system's complexity and are responsible for changing system's complexity level (Meyer, 2007, p. 26). The literature results are subdivided by Meyer (2007) in 2 categories:

- Category #1: General complexity drivers and their influences on increasing complexity in a company.
- Category #2: Major complexity drivers and their influences regarding logistics.

According to Meyer (2007, pp. 29-31), the complexity drivers and their influences in category #1 are based on variant management. They concern mostly product complexity and product complexity's area of influence. As a result of the literature research, Meyer (2007, pp. 182-183) identifies 19 literature sources and describes 127 complexity drivers in 14 driver categories. In summary, Meyer (2007, pp. 182-183) offers a table, showing the identified complexity drivers, their appearances in literature and their influences. However, he does not describe a comparison between the different literature sources. Furthermore, he focused his research only on general complexity drivers and complexity drivers regarding logistics. Complexity drivers in other parts along the value chain are not described and compared with his findings. In addition, Meyer (2007) does not describe specific approaches for complexity driver's identification, operationalization and visualization. No research questions, databases, search terms and synthesizing methods are determined.

Serdarasan (2011, pp. 793-794; 2013, pp. 534-535) published 2 review papers concerning supply chain complexity drivers. The first paper was published in the proceedings of the 41st International Conference on Computers & Industrial Engineering in 2011. The second paper was published in the journal of Computers & Industrial Engineering in 2013. In her papers, Serdarasan (2011, p. 792; 2013, p. 533) reviews the "typical complexity drivers that are faced in different types of supply chain and presents the complexity driver and solution strategy pairings in the form of a matrix". The information was extracted from real-life supply chain situations and gathered from multiple existing sources, such as interviews, observations, reports and archives.

In the first paper, Serdarasan (2011, p. 792) reviews the literature on supply chain complexity drivers, because in her opinion, this is the first step in developing a clear strategy for complexity handling. Before reviewing the literature, Serdarasan (2011, pp. 793-794) analyzed the 3 different types of supply chain complexity (static, dynamic and decision making) and describes her understanding of the term complexity drivers. In her understanding, "a supply chain complexity driver is any property of a supply chain that increases its complexity" and corresponds with the different types of supply chain complexity (Serdarasan, 2011, pp. 793-794). Furthermore, Serdarasan (2011, p. 793) classifies the complexity drivers "according to their origin in internal, supply/demand interface and external/environmental drivers". In total, 23 literature sources are identified and 27 complexity drivers are described in the 3 driver categories internal, supply/demand interface and external. In addition, Serdarasan (2011, pp. 794-795) gives an overview of 27 different solution strategies for handling specific complexity drivers. However, the information about all references and the systematic review results are not described, because of "space restrictions" in the conference paper (Serdarasan, 2011, p. 795). In summary, in her first paper Serdarasan (2011, pp. 793-795) offers an overview, showing the identified complexity drivers and their overall origin categories and describes some solution strategies for complexity driver's handling. However, she does not describe a comparison between the different literature sources and their findings. Furthermore, she focused her research only on supply chain complexity drivers. Complexity drivers in other parts along the value chain are not described and compared with her findings.

In the second paper, Serdarasan (2013, p. 533) enhances the content of her first paper and reviews the "typical complexity drivers that are faced in different types of supply chains and present the complexity driver and solution strategy pairings" based on good industry practices. Analogously to the first paper, Serdarasan (2013, p. 534) distinguishes in the first step the supply chain complexity in the already mentioned 3 types: Static, dynamic and decision making. Then, she describes her understanding of the term complexity drivers and combines it with the different types of supply chain complexity and their origin (internal, supply/demand interface and external/environmental). In the next step, Serdarasan (2013, p. 535) analyzes the identified 38 literature sources, focused on supply chain complexity according to their type and origin. As a result of the analysis, Serdarasan (2013, pp. 534-535) states that the related literature is mostly focused on internal and interface complexities. The number of studies dealing with external complexity drivers is smaller, because "external drivers are outside the system boundary of the supply chain". According to the 3 types of supply chain complexity, the literature is mostly focused on static and dynamic types. Decision making complexity is also much less in the focus of literature. Based on her literature research, Serdarasan (2013, p. 534) develops a classification of supply chain complexity drivers according to their type and origin. In her publication, 32 supply chain complexity drivers are described in 9 complexity driver categories. For complexity drivers handling, Serdarasan (2013, pp. 535-536) extends the overview of different solution strategies from 27 in the first paper to 33 in the journal paper. Summarizing the second paper, Serdarasan (2013, pp. 534-535) presents a table, consisting of the identified complexity drivers, which were clustered according to their type and origin. Furthermore, she compares the different literature sources and their findings to identify commonalities and differences. Analogously to the first paper, Serdarasan (2013) focuses her research only on supply chain complexity drivers. Complexity drivers in other parts along the value chain are not described and compared with her findings.

In addition, Serdarasan (2011; 2013) does not describe specific approaches for complexity driver's identification, operationalization and visualization in her 2 papers. Beyond, no research questions, databases, search terms and synthesizing methods are determined.

The objective of Wildemann and Voigt's research (Wildemann and Voigt, 2011, pp. 40-43) is to identify internal and external complexity drivers in manufacturing companies with the aim of quantifying company's product portfolio, process and structure complexity. As a result, a company's complexity profile can be compared to other companies. The basis of Wildemann and Voigt's (2011, pp. 44-52, 63-72, 114-119) overview is a comprehensive literature and case study analysis about complexity drivers. Before starting the literature research, Wildemann and Voigt (2011, pp. 44-52) analyzed the term complexity extensively to develop their own definitions for internal and external complexity. According to Wildemann and Voigt (2011, p. 52), external complexity is the sum of all parameters in a company that cannot be influenced or can only be indirectly influenced. External complexity is a constitutive trait for a company's processes that the product program and the company's structure exhibit. Their dynamics are only predictable to some extent. Internal complexity is the sum of all material and immaterial units in a company and their static and dynamic links that express the external requirements within the company's borders. For complexity driver's understanding, Wildemann and Voigt (2011, pp. 65-66) cite the definition of Piller that complexity drivers are a "phenomenon, which actuate a system to increase their own complexity". Based on this understanding, Wildemann and Voigt (2011, pp. 63-72) perform a comprehensive literature research focused on complexity drivers and separate the identified complexity drivers according to their origin into internal and external categories. As a result of their literature research, Wildemann and Voigt (2011, pp. 44-46, 64-72) identify 17 literature sources about complexity drivers and identify 32 external and 63 internal complexity drivers, which are allocated in 11 driver categories. Wildemann and Voigt (2011, p. 71) criticize that literature's assignment of complexity drivers to different driver clusters show some contradictions. In addition to their literature research, Wildemann and Voigt (2011, pp. 114-119) analyze 27 case studies to extend literature's results about complexity drivers with complexity drivers identified in practice. The case studies comprise different branches to provide a differentiated overview about external drivers and their internal impacts. In summary, 115 different complexity drivers are identified and clustered according to 9 main driver categories (3 external and 6 internal). Then, the results are visualized in a "complexity driver tree" and evaluated in a further empirical study to identify the most relevant complexity drivers for practice. As a result, the total amount of complexity drivers is condensed to an amount of complexity drivers, which is easy to handle in practice. Based on expert interviews, Wildemann and Voigt (2011, pp. 116-124, 129-170) finally identify 10 relevant external and 20 relevant internal complexity drivers. The concentrated complexity drivers are the basis for an additional empirical research by online questioning. Within the questioning, the trends of internal and external complexity drivers, their relevance and influences on company's processes are investigated. The results from literature and empirical research are the inputs for the development of a complexity index (Wildemann and Voigt, 2011, pp. 171-380). In summary, Wildemann and Voigt (2011, pp. 63-72, 114-124) present in the first step a literature overview about complexity drivers general in manufacturing companies. The identified drivers are clustered according to their origin in internal and external drivers. The authors compare the different literature sources and their findings to identify commonalities and differences. Then, they compare the literature results with the results from empirical research to extend the total amount of complexity drivers. The results are visualized in a complexity tree. The practical relevant drivers are identified through expert interviews. However, Wildemann and Voigt (2011) focus their research only on general complexity drivers. Complexity drivers in other parts of the company and along the value chain are not described and compared with their findings. In addition, Wildemann and Voigt (2011) do not describe specific approaches for complexity driver's identification and operationalization. Only 1 method for complexity driver's visualization is described. For literature research, no research questions, databases, search terms and synthesizing methods are determined.

Table 5 summarizes the results of our analysis according to the previous literature studies about complexity drivers. The table shows a list of existing reviews and overviews/surveys and gives an overview of their focus, research period and results about complexity drivers. Furthermore, the identified literature studies are analyzed and evaluated based on the requirements of a systematic, explicit and reproducible literature review, described by Fink (2014, p. 3).

The evaluation is based on the following 2 criteria: Fulfilled (+ +) and not fulfilled (-). Table 5 gives an overview about the determination of the 2 evaluation criteria in the following 2 categories:

- Determination of research questions, databases, search terms and synthesizing methods.
- Comparison of literature findings with other literature sources or empirical research data.

As a result of Table 5 and the analysis of the previous literature studies, the existing studies cover complexity drivers on specific issues, such as logistics, supply chains or general in manufacturing companies (see Table 5).

A vast number of literature sources and complexity drivers in the referred field is covered in these literature studies. Although, a systematic, explicit and reproducible method for identification, evaluation and synthesizing the existing literature about complexity drivers is not described (Fink, 2014, p. 3). In the previous literature studies, no research questions, databases, search terms and synthesizing methods are described (see Table 5). Furthermore, the literature findings are only compared in 2 of the 4 studies to identify commonalities and differences to improve reader's understanding in a particular field of research. These are essential to determine the current state of knowledge about a particular research issue in a literature review according to Fink (2014, pp. 3-5).

The existing literature studies only describe complexity drivers in a specific field of manufacturing companies. A more general overview about complexity drivers in manufacturing companies and along the value chain does not exist yet. Furthermore, no different definitions of complexity drivers are identified, compared and discussed in the previous literature studies. Meyer (2007, p. 26), Serdarasan (2011, p. 793; 2013, p. 534) and Wildemann and Voigt (2011, pp. 63-64) provide only 1 definition for complexity drivers. In our opinion, a more extensive point of view is necessary to identify all characteristics of complexity drivers. Complexity driver's understanding is the first step in managing complexity (see subsection 3.3.1). In the existing studies, no approaches for complexity driver's identification or operationalization are described. A specific and target-oriented complexity management is based on identification, operationalization and visualization of a system's complexity drivers (see subsection 3.3.2). For science and practice, it is important to know that different methods for complexity driver's identification, operationalization and visualization exist in literature. Only Wildemann and Voigt (2011, pp. 116-117) describe a method for complexity driver's visualization in their research paper. However, this method is not applicable in all cases. Thus, further methods for complexity driver's visualization are required.

Table 5: List of existing reviews or overviews regarding complexity drivers and their results

Author(s)		Meyer (2007, pp. 182-183)	Serdarasan (2011, pp. 793-795)	Wildemann and Voigt (2011, pp. 44-52, 64-72, 114-170)	Serdarasan (2013, pp. 534-535)
Type of literature study		Overview	Review	Overview	Review
Publication's language		German	English	German	English
Focus	General in manufacturing companies	•		•	
	Product Development				
	Procurement/Purchasing				
	Logistics	•			
	Production				
	Order Processing/Distribution/Sale				
	Internal Supply Chain		•		•
	Remanufacturing				
	General in Value Chain				
Research period		1992 - 2004	1998 - 2011	1991 - 2010	1992 - 2011
Literature review's results: Amount of ...	Identified literature sources	19	25	17	38
	Complexity driver's definitions	1	1	1	1
	Described complexity drivers	127	27	95	32
	Complexity driver categories	14	3	11	9
Determination of ... by the author(s)	Research questions	-	-	-	-
	Databases	-	-	-	-
	Search terms	-	-	-	-
	Synthesizing methods	-	-	-	-
Literature findings' comparison with...	Other literature sources	-	-	+ +	+ +
	Empirical research data	-	-	+ +	-

Evaluation criteria:

fulfilled (+ +)	Precise research questions, databases, search terms and synthesizing methods are described. The literature findings are compared with other literature sources or empirical research data.
not fulfilled (-)	Precise research questions, databases, search terms and synthesizing methods are not described. The literature findings are not compared with other literature sources or empirical research data.

In our research, we want to close the referred gaps by a systematic, explicit and reproducible literature review about complexity drivers general in manufacturing companies and along the value chain. According to literature, the existing studies are only focused on specific issues, such as logistics, supply chain or general in the company (see Table 5). One of this chapter's purposes is to present an overview about complexity drivers in all aspects along the value chain and in manufacturing companies in attempt to close this literature gap. Furthermore, the results are compared with each other to identify commonalities and differences between complexity drivers general in manufacturing companies and along the value chain. In addition, we identify and analyze all existing definitions of complexity drivers and develop a new overall definition to increase the understanding of complexity drivers. Our objective is to fulfill all requirements of a literature review in general.

To achieve this aim, the identified 235 literature sources (N_T) were analyzed in detail (see Figure 5). In total, 23 papers are focused only on general information about complexity drivers (N_O). As already mentioned, 212 papers contain information about complexity drivers in manufacturing companies and along the value chain (N_I). Within these 212 papers, 108 literature parts can be identified that deal with complexity drivers general in manufacturing companies (N_G). Furthermore, 115 literature parts are focused on complexity drivers along the value chain (N_{VC}). As a result, 11 papers describe both parts ($N_G \cap N_{VC}$).

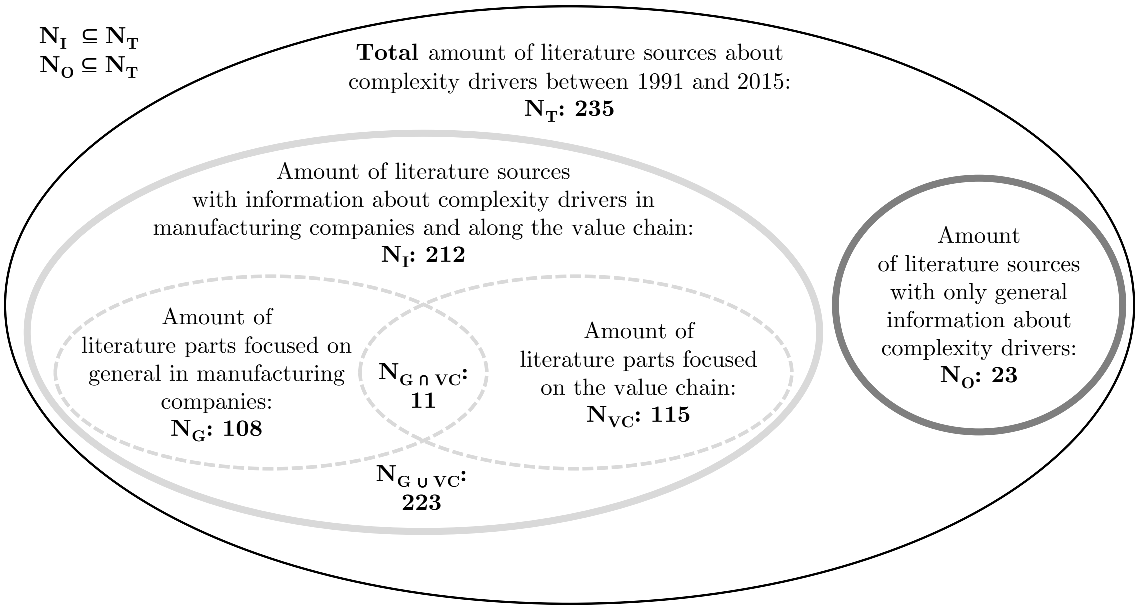


Figure 5: Overview about literature analysis' results

After identification and segmentation of the researched literature, the next step was to analyze the overall trend of all literature regarding complexity drivers in manufacturing companies and along the value chain (see Figure 6). Further, the results were separated in German and English publications. Figure 6 presents the total amount of publications regarding complexity drivers, published in the time period 1991 to 2015.

The represented trend shows an increased interest in complexity drivers throughout the last 10 years, because they are the basis for a target-oriented complexity management. It can be derived that complexity drivers attract more and more attention in scientific research. Another reason for the increase in numbers of literature sources might be the increased amount of included literature sources in databases over time. For example, the database EBSCOhost enhanced their connection to other databases over the last years and thus it covers more and more books, journals and conference papers. Between 2004 and 2015, 74% of all publications were published. Furthermore, 72% of all publications were published in German. However, the amount of English publications increased continuously in the last 6 years.

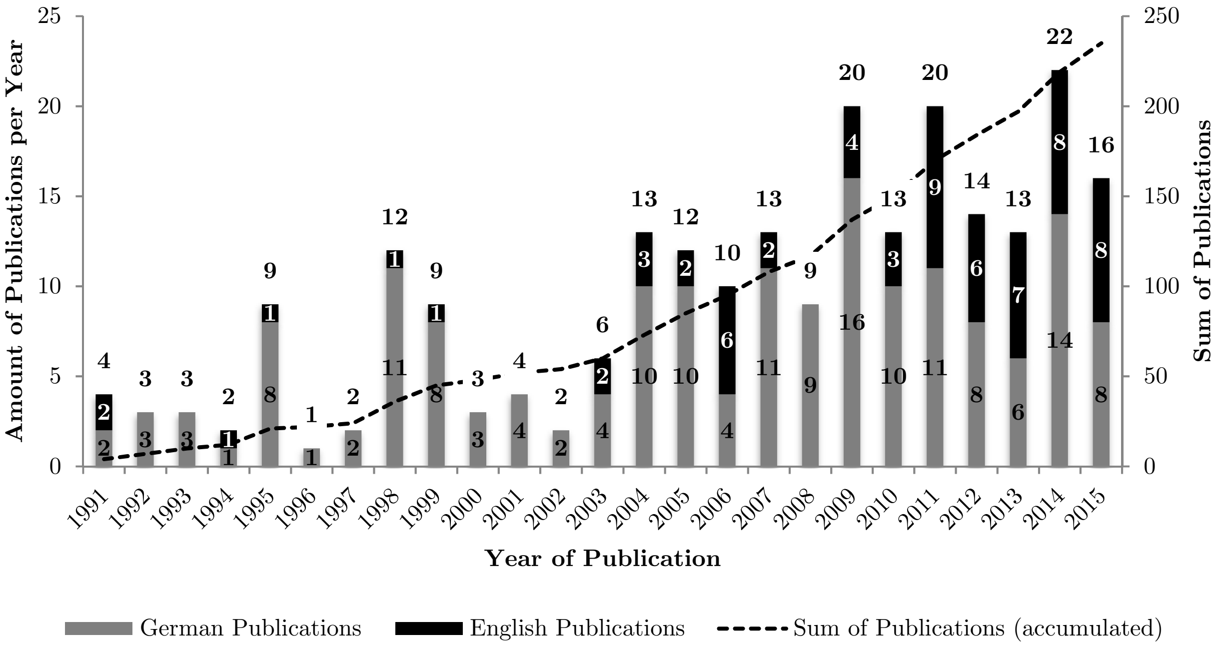


Figure 6: Trend of all literature sources about complexity drivers between 1991 and 2015

As already mentioned, 212 papers (90% of all literature sources) describe specific complexity drivers in manufacturing companies and along the value chain. After analyzing and synthesizing these 212 papers, we identified 223 different literature parts with complexity drivers in manufacturing companies and along the value chain (see Figure 5 and Table 46 in the appendix). Thus, 11 authors have described more than one field of complexity drivers in their publications (see Figure 5). For example, Mayer (2007, p. 109), Meyer (2007, p. 101) and Lasch and Gießmann (2009a, p. 201) describe complexity drivers general in manufacturing companies and drivers in the field logistics in their publications.

With regard to the existing literature, the data from Figure 6 was separated in 2 categories to allow the researchers an overview about the different trends in literature regarding complexity drivers (see Figure 7) and their increasing importance for manufacturing companies:

- General complexity drivers in manufacturing companies (108 parts).
- Complexity drivers along the value chain (115 parts).

Furthermore, the different trends in literature show the current research direction and give an implication for gaps and future research.

Figure 7 shows these referred trends during the last 25 years. In total, 108 literature parts (48%) concern general complexity drivers in manufacturing companies. Most of these publications were published between the years 1998 and 2010 (70%). On the other side, 115 publications describe complexity drivers along the value chain. In the last 10 years, 83% of the publications about complexity drivers along the value chain were published. Thus, there is an increasing interest in complexity drivers along the value chain in scientific literature.

A comparison between the focus of publications in the early years with the focus of publications during more recent years shows that complexity drivers are now described more in detail regarding different parts along the value chain. This indicates that complexity drivers gain more and more importance in scientific research.

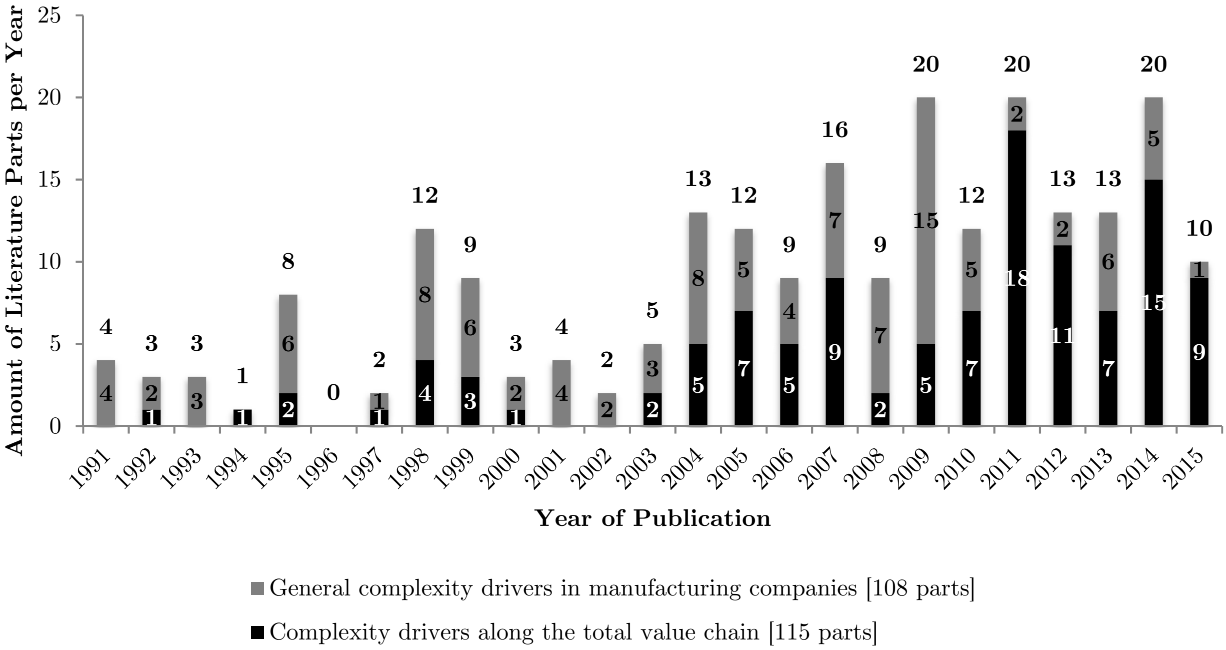


Figure 7: Trend of literature about general complexity drivers in manufacturing companies and complexity drivers along the value chain in manufacturing companies between 1991 and 2015

According to Wildemann (2011, p. 86), Schönsleben (2011, pp. 8-9), Blecker and Kersten (2006, pp. V-VI) and Kaluza, Bliem and Winkler (2006, pp. 3-11), we separated the value chain in 7 different fields: Product Development (PD), Procurement/Purchasing (PC), Logistics (L), Production (PR), Order Processing/Distribution/Sale (OPD), Internal Supply Chain (SC) and Remanufacturing (R).

Furthermore, we extend this separation by introducing the field General in Value Chain (VC), because in our research, we found out that some authors described complexity drivers along the value chain in general.

To allow an overview about the trend of literature in the 8 different fields of the value chain, the data from Figure 7 in the category complexity drivers along the value chain was separated. Table 6 gives an overview about the amount of literature during the last 25 years in particular fields of the value chain. The table also shows that the amount of publications about complexity drivers in all 8 different fields has increased. Thus, there is an increasing interest in complexity drivers over the last 10 years.

The main focus is on internal supply chain (23%), production (22%), logistics (16%), product development (15%) and order processing/distribution/sale (11%). In summary, 87% of all publications are focused on these fields. This shows that these fields are identified by several researches as important sources of complexity in the company and were analyzed precisely within the last 25 years. Other important sources of complexity are the fields procurement, remanufacturing and general in value chain, but only 13% of the publications are focused on these fields. With a percentage of 3.5%, the field remanufacturing has the smallest proportion of all publications. The analysis shows that in the fields procurement, remanufacturing and general in value chain future research is necessary, because these fields are also important sources of complexity in manufacturing companies. Based on the systems theory, complexity occurs not only in specific parts of a system. Instead, handling complexity requires a consideration of all parts and their interdependencies in a system.

Table 6: Overview about the amount of literature in particular fields of the value chain between 1991 and 2015

Field	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total (row)	%
PD								2					1	1		1	1			1		4		4	2	17	14.8%
PC									1						1		1			1	1			1		6	5.2%
L				1	2			1		1				1	2	1	2		1	2	2			1	1	18	15.7%
PR								1	1					1	2		1	1	2	1	5	1	1	5	3	25	21.7%
OPD		1					1		1							1	1			1	1	3	1	1	1	13	11.3%
SC														2	2	2	2		2	1	7	1	4	1	2	26	22.6%
R																					2	1	1			4	3.5%
VC													1					1			2			1	1	6	5.2%
																									Total:	115	100%

Explanation to Field:

PD	Product Development	PC	Procurement/Purchasing	L	Logistics
PR	Production	OPD	Order Processing/Distribution/Sale	SC	Internal Supply Chain
R	Remanufacturing	VC	General in Value Chain		

3.3.2 Definition of complexity drivers

Complexity management in the company requires identification and controlling of the essential complexity drivers (Schuh, 2005, p. 8; Budde and Golovatchev, 2011, p. 2), because complexity drivers can lead to increasing complexity (Blecker *et al.*, 2005, p. 59). Before identification, it is necessary to understand, what a complexity driver is (Meyer, 2007, pp. 21-29; Kolbusa, 2013a, p. 83). Lucae, Rebentisch and Oelmen (2014, p. 654) argue that it is important "to better understand the complexity drivers that are impeding reliable planning and common planning mistakes made in large-scale engineering programs". In literature today, there is no universal understanding of the term “complexity driver” (Meyer, 2007, pp. 21-29). Buob (2010, pp. 15-22, 52) argues that the term “complexity driver” cannot be defined extensively.

Answering the first research question, we analyzed the identified literature. Several different definitions exist in literature, but they all tend to the same content and seem alike and not different (see Table 7).

To describe the term complexity driver, the first step is to understand, what a driver is in general. In the Business Dictionary (2014) 3 different definitions of the term “driver” exist:

- Condition or decision that causes subsequent conditions or decisions to occur as a consequence of its own occurrence.
- Element of a system that has a major or critical effect on the associated elements or the entire system.
- Root cause of a condition or measurement.

These 3 different definitions show that a driver is responsible for a situation or condition and has an impact on it. Table 7 presents several definitions about complexity drivers that exist in literature and their authors. In total, 36 literature sources describe different definitions of complexity drivers, 26 sources are written in German and 10 in English. Generally, the definitions can be separated in 5 main categories: factors, indicators, sources, parameters/variables and symptoms/phenomenon, which influence a system’s complexity. The different complexity driver’s categories are filled with information from German and English written studies. Most of the different driver’s categories comprise information from both languages. Only the category ‘sources’ is described only in German written literature studies. Further, it can be seen that the English literature sources are concentrated on the categories ‘factors’ and ‘indicators’. For literature’s synthesizing, we analyzed the different statements or definitions of the authors and summarized them in a superior statement, which is described in Table 7.

Table 7: Definitions of complexity drivers in scientific literature

Complexity driver's category	Author(s)	Definition *The author(s) describe(s) complexity drivers as...*
Factors	Schmidt (1992, p. 14)[1]; Reiß (1993a, p. 3)[1]; Fleck (1995, p. 178)[1]; Höge (1995, pp. 5-6)[1]; Bohne (1998, pp. 58-59)[1]; Puhl (1999, p. 31)[1]; Berens and Schmitting (1998, p. 98)[1]; Fehling (2002, p. 68)[1]; Giannopoulos (2006, pp. 154-156)[2]; Buob (2010, pp. 20-21)[1]	...*factors*, which influence a system's complexity.
	Piller and Waringer (1999, pp. 5-6)[1]	...*factors*, which increase a system's complexity.
	Hanenkamp (2004, pp. 62-66)[1]; Meyer (2007, p. 26)[1]; Lammers (2012, pp. 31-33)[1]	...*factors*, which influence the system's complexity and are responsible for changing system's complexity level.
	Schuh, Gartzen and Wagner (2015, p. 2)[2]	...*factors*, which may create high complexity.
	Christ (2015, p. 58)[1]	...*factors*, which are responsible for resource wasting ('Muda') in the company.
Indicators	Warnecke and Puhl (1997, p. 360)[1]; Puhl (1999, p. 31)[1]; Perona and Miragliotta (2004, pp. 111-114)[2]; Giannopoulos (2006, pp. 154-156)[2]; Leeuw, Grotenhuis and Goor (2013, pp. 960-969)[2]	...*indicators*, which influence a system's complexity.
	Payne and Payne (2004, pp. 116-119)[2]	...*indicators* for complexity, but they do not describe all characteristics of the phenomenon.
	Rudzio, Apitz and Denkena (2006, p. 53)[1]	...*indicators*, which indicate high complexity in the company.
Sources	Wildemann (1999b, pp. 31-32)[1]	...*sources*, which are responsible for a system's complexity.
	Gießmann and Lasch (2010, p. 155)[1]	...*sources*, which influence the target achievement in the company.
Parameters/ Variables	Biersack (2002, p. 52)[1]	...*parameters*, indicators or factors, which help to define the characteristics and economic effects of a system's complexity.
	Schließmann (2010, p. 59)[1]; Gerschberger *et al.* (2012, pp. 1015-1016)[2]	...*parameters*, which are responsible for a system's complexity.
	Schwenk-Willi (2001, pp. 27-28)[1]	...*variables*, which depend on one another, without complete reduction to another one.
Symptoms/ Phenomenon	Höge (1995, pp. 5-6)[1]	...*symptoms* of a system's complexity.
	Dehnen (2004, p. 32)[1]; Götzfried (2013, pp. 35-36)[2]	...*phenomenon*, which actuates a system to increase own complexity.
Others	Dehnen (2004, p. 47)[1]	...*dimensions* of complexity.
	Moos (2009, p. 54)[1]	...*forces*, which encourage a system's complexity and are located on the interface between external and internal complexity.
	Serdarasan (2011, p. 793; 2013, p. 534)[2]	...*properties*, which increase a system's complexity.
Language of literature source:	1 German (Number: 26)	2 English (Number: 10)

After analyzing and synthesizing the existing literature and the described different definitions of complexity drivers, we come to the conclusion that an overall definition is required to summarize all collected information in 1 definition.

For the development of the new definition, we proceeded in the following way: In the first step, we analyzed the characteristics of a definition itself. The first common statement of a definition is by Aristoteles. He states that a definition is a "statement, which contains the essence of the object that is to be defined" (cited in Dubislav, 1981, pp. 3-4). The Encyclopedia of Language and Linguistics describes a definition as a "statement of the meaning of a word, term, or symbol" (Brown *et al.*, 2006, p. 399). The encyclopedias of BROCKHAUS and DIE ZEIT extend the mentioned definition and describe a definition as a "determination of a term by specifying the essential attributes" (BROCKHAUS, 2006, p. 366; DIE ZEIT, 2005, p. 277). According to the Encyclopedia of Language and Linguistics, a "traditional definition consists of a genus term and any of a number of differentia. The genus term answers the question, 'What sort of thing is it?'. The differentia distinguishes it from members of related sets" (Brown *et al.*, 2006, p. 399). The encyclopedia of DIE ZEIT describes the genus term as the "generic term (genus proximum)". The differentia specifies the differences in nature (DIE ZEIT, 2005, p. 277).

Based on definition's structure in literature, in the next step, we analyzed the existing definitions and statements according to their structure. In all definitions or statements, the term "complexity driver" is the genus term. The terms "factor" or "indicator" or "source" or "parameter" etc. are the hypernym of a class. The differentia describes the characteristics and the essential attributes of the definition and "distinguish it from members of related sets" (Brown *et al.*, 2006, p. 399). The statements "[...] which influence a system's complexity" or "[...] which indicate high complexity in company" etc. are the identified differentia in our research.

In literature, several hypernyms for complexity drivers are presented: Factor, indicator, source, parameter, variable, symptom, phenomenon, dimension, force and property. However, the meanings of these terms are different (see Table 8). Thus, we analyzed these terms and compared the meanings with the general understanding of a complexity driver, described in literature. According to Schuh (2005, p. 8), Meyer (2007, p. 26) and Krizanits (2015, p. 44), complexity drivers are causing something or have an effect or influence on something. Then, we evaluated the existing meanings based on the following 3 evaluation criteria:

- Fulfilled (+ +): Content covers the general understanding of a complexity driver in total and contains the 2 terms cause and influence.
- Partial fulfilled (+): Content covers the general understanding of a complexity driver partially and contains 1 of the 2 terms cause and influence.
- Not fulfilled (-): Content does not cover the general understanding of a complexity. The 2 terms cause and influence are not described.

The terms, which fulfill the general understanding of a complexity driver are marked (see Table 8). The Oxford Learner's Dictionaries define the different hypernyms presented in Table 8. As a result, only the term factor consists the attributes cause and influence. Thus, we come to the conclusion that the term factor is the suitable hypernym for complexity drivers.

Table 8: Definitions of complexity driver's hypernyms

Complexity driver's hypernyms	Definition according to the Oxford Learner's Dictionaries	Evaluation result
Factor (Oxford Learner's Dictionaries, 2016b)	"**One of several things that cause or influence something**."	+ +
Indicator (Oxford Learner's Dictionaries, 2016d)	"A sign that shows you what something is like or how a situation is changing."	-
Source (Oxford Learner's Dictionaries, 2016h)	"A person or thing that causes something, especially a problem."	+
Parameter (Oxford Learner's Dictionaries, 2016e)	"Something that decides or limits the way in which something can be done."	-
Variable (Oxford Learner's Dictionaries, 2016j)	"Able to be changed."	-
Symptom (Oxford Learner's Dictionaries, 2016i)	"A sign that something exists, especially something bad."	-
Phenomenon (Oxford Learner's Dictionaries, 2016f)	"A fact or an event in nature or society, especially one that is not fully understood."	-
Dimension (Oxford Learner's Dictionaries, 2016a)	"The size and extent of a situation."	-
Force (Oxford Learner's Dictionaries, 2016c)	"The strong effect or influence of something."	+
Property (Oxford Learner's Dictionaries, 2016g)	"A quality or characteristic that something has."	-
Explanation for evaluation criteria:	+ + fulfilled + partially fulfilled - not fulfilled	

In the next step, we analyzed the identified differentia and compared them with each other to identify commonalities and differences. Then, we clustered the differentia according to their content. In literature, 16 different differentia are described. Some differentia are used more often than others to describe complexity drivers. Table 9 presents the 16 differentia, their literature's occurrence and the results of differentia's clustering.

In summary, the 16 differentia can be clustered in 5 groups. The first group describes that complexity drivers have principally an influence on system's complexity. Group #2 concretizes the statement of group #1 and concludes that complexity drivers have not only an influence on system's complexity, but they are responsible for increasing the complexity level in a system. Group #3 describes further that complexity drivers have a direct influence on company's target achievement. Beyond, complexity drivers are influenced by one another, that is by internal or external drivers, and cannot be reduced completely to another one (see Group #4). Furthermore, complexity drivers help to define the characteristics or the phenomenon of a system's complexity (see Group #5).

Based on the 5 differentia groups and the identified hypernym term "factor", we developed the following general complexity driver definition:

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. Complexity drivers are influenced by one another, that is by internal or external drivers, and cannot be reduced completely to another one.

Table 9: Overview of complexity driver's differentia and their literature's occurrence

Type	In literature described complexity driver's differentia	Number of authors that use this differentia	Clustering of the identified complexity driver's differentia
#1	[...], which influence a system's complexity.	18	[...], which influence a system's complexity.
#2	[...], which are responsible for a system's complexity.	3	
#3	[...], which encourage a system's complexity.	1	
#4	[...], symptoms of a system's complexity.	1	
#5	[...], dimension of complexity.	1	
#6	[...], are responsible for changing system's complexity level.	3	[...], which are responsible for increasing system's complexity level.
#7	[...], which increase a system's complexity.	3	
#8	[...], which may create high complexity.	1	
#9	[...], which indicate high complexity in the company.	1	
#10	[...], which actuate a system to increase own complexity.	2	
#11	[...], which are responsible for resource wasting in the company.	1	[...], which influence company's target achievement.
#12	[...], which influence the target achievement in the company.	1	
#13	[...], which depend on one another, without complete reduction to another one.	1	[...], are influenced by one another (internal or external) and cannot be reduced completely to another one.
#14	[...], located on the interface between external and internal complexity.	1	
#15	[...], but they do not describe all characteristics of the phenomenon.	1	[...], help to define the characteristics or the phenomenon of a system's complexity.
#16	[...], which help to define the characteristic and economic effects of a system's complexity.	1	

3.3.3 Approaches for identification, operationalization and visualization of complexity drivers

Complexity drivers have an influence on companies and the total value chain (Schuh, 2005, pp. 8-19). A specific and target-oriented complexity management is based on identification, operationalization and visualization of a system's complexity drivers. Keuper (2004, pp. 82-83) describes that handling a company's complexity depends on the complexity drivers. Schmitt, Vorspel-Rüter and Wienholdt (2010, pp. 843-844) explain that the identification and classification of measurable complexity drivers is the baseline for complexity reduction. Further, Schwenk-Willi (2001, p. 27) and Sun and Rose (2015, pp. 1211-1215) argue that complexity drivers are necessary for operationalization and quantification of complexity. Greitemeyer, Meier and Ulrich (2008) describe that complexity drivers are responsible for complexity costs. Moreover, they are necessary for the creation of complexity key performance indicators. Therefore, it is required to identify and evaluate the relevant drivers (Greitemeyer, Meier and Ulrich, 2008, pp. 37-39).

According to the quote “If you can’t measure it you can’t manage it.” (Grote, Kauffeld and Frieling, 2006, p. 4), it is important to quantify complexity drivers and their effects (Haumann *et al.*, 2012, p. 108; Schwenk-Willi, 2001, pp. 27-31; Steinhilper *et al.*, 2012, pp. 361-362) from a holistic view (Sun and Rose, 2015, p. 1211). For quantifying complexity drivers and their effects, it is necessary to identify theoretically possible complexity drivers first. The next step is to identify practically relevant complexity drivers (Haumann *et al.*, 2012, pp. 108-111; Steinhilper *et al.*, 2012, pp. 362-364), for example within an empirical research (Wildemann and Voigt, 2011, pp. 113-170).

To answer the second research question, we analyzed the identified literature sources according to general approaches for complexity driver’s identification, operationalization and visualization. Parry, Purchase and Mills (2011, p. 68) argue that recognition and identification of the complexity drivers “enable managers to realize value” and “reducing complexity where possible”. Ehrenmann (2015, p. 15) argues further that complexity driver’s analysis enables first indications about the success of process’ changing.

3.3.3.1 Identification of complexity drivers

As a result of literature analysis, 37 authors describe 21 different approaches for complexity driver’s identification in their papers. Most of the identified approaches are published in German written studies (68%). More than 50% of the approaches are applied for complexity driver’s identification general in manufacturing companies. Based on the literature analysis, the most applied approaches are expert interviews, process analysis and system analysis. Table 10 presents an overview of the identified approaches found in literature and the fields, on which they are focused. Some authors combine different approaches to identify complexity drivers. Furthermore, the identified approaches are clustered into 7 fields based on their principle to increase transparency. An evaluation of the different approaches regarding their practical uses was not conducted. This is a mere reflection of the approaches found in literature. Such an evaluation can be an implication for further research.

Table 10: Overview about approaches for identification of complexity drivers in particular fields (Part A)

Explanation according to focus:

G	General in manufacturing companies
PD	Product Development
PC	Procurement/Purchasing
L	Logistics
PR	Production*
OPD	Order Processing/Distribution/Sale*
SC	Internal Supply Chain
R	Remanufacturing
VC	Total Value Chain

* No approaches for identification of complexity drivers were found in this field.

Language of literature source:

[1] German (Number: 25)
[2] English (Number: 12)

Approach(es) based on...
1: Questioning
2: Process & Observation
3: System
4: Influence & Dependency
5: Documents & Literature
6: Classification
7: Others

	1			2				3		4					5			6	7			
Author(s)	Expert Interviews	Workshops	Questionnaire	Process Analysis	Process Observation	Activity-based Costing	Situation Observation	System Analysis	Structure Analysis	Influence Analysis	Cause-Effect-Analysis (Ishikawa)	Dependence Analysis	Failure Mode and Effect Analysis	Variant Mode and Effect Analysis	Analyzing of Documents	Complexity Diaries	Literature Research	ABC-Analysis	Factor Analysis	Cost-Benefit Analysis	Creativity Techniques	Focus
Vizjak and Schiffers (1996, p. 9) [1]																				•		G
Warnecke and Puhl (1997, p. 360) [1]				•																		G
Rosemann (1998, p. 61) [1]						•																G
Puhl (1999, pp. 31-33) [1]								•														G
Meier, Hanenkamp and Bäcker (2003, pp. 10-11) [1]												•										G
Hanenkamp (2004, pp. 66-67) [1]			•																			G
Giannopoulos (2006, p. 154) [2]		•																				G
Größler, Grübner and Milling (2006, pp. 261-264) [2]																			•			G
Kohagen (2007, p. 20) [1]										•												G
Krause, Franke and Gausemeier (2007, pp. 16-19) [1]								•														G
Greitemeyer, Meier and Ulrich (2008, pp. 38-39) [1]										•												G
Lasch and Gießmann (2009b, p. 116) [1]											•		•								•	G
Bayer (2010, p. 9) [1]	•																		•			G
Schließmann (2010, p. 59) [1]								•														G
Schmitt, Vorspel-Rüter and Wienholdt (2010, pp. 843-844) [1]								•														G
Schawel and Billing (2011, p. 111) [1]				•					•													G
Collinson and Jay (2012, pp. 42-47) [2]	•	•						•								•						G
Steinhilper *et al.* (2012, pp. 361-364) [1]	•			•																		G
Serdarasan (2013, p. 533) [2]							•															G

Table 10: Overview about approaches for identification of complexity drivers in particular fields (Part B)

Explanation according to focus:

- G General in manufacturing companies
- PD Product Development
- PC Procurement/Purchasing
- L Logistics
- PR Production*
- OPD Order Processing/Distribution/Sale*
- SC Internal Supply Chain
- R Remanufacturing
- VC Total Value Chain

* No approaches for identification of complexity drivers were found in this field.

Language of literature source:

[1] German (Number: 25)
[2] English (Number: 12)

Approach(es) based on...

1: Questioning
2: Process & Observation
3: System
4: Influence & Dependency
5: Documents & Literature
6: Classification
7: Others

Author(s)	1			2				3		4					5			6	7			
	Expert Interviews	Workshops	Questionnaire	Process Analysis	Process Observation	Activity-based Costing	Situation Observation	System Analysis	Structure Analysis	Influence Analysis	Cause-Effect-Analysis (Ishikawa)	Dependence Analysis	Failure Mode and Effect Analysis	Variant Mode and Effect Analysis	Analyzing of Documents	Complexity Diaries	Literature Research	ABC-Analysis	Factor Analysis	Cost-Benefit Analysis	Creativity Techniques	Focus
Krumm and Schopf (2005, p. 47) [1]														•								PD
Bosch-Rekveldt *et al.* (2015, pp. 1084-1086) [2]			•																			PD
Wildemann (1999a, p. 65) [1]								•										•				PC
Weber (1994, p. 24) [1]				•																		L
Lasch and Gießmann (2009a, pp. 223-227) [1]		•																				L
Kersten, Lammers and Skirde (2012, pp. 21-25) [1]								•									•					L
Reuter, Prote and Stöwer (2015, p. 9) [1]																	•					PR
Schott, Horstmann and Bodendorf (2015, pp. 33-36) [2]																	•					PR
Perona and Miragliotta (2004, pp. 106-107) [2]	•																					SC
Geimer (2005, pp. 40-43) [1]	•																					SC
Vickers and Kodarin (2006, p. 2) [2]	•																					SC
Ballmer (2009, p. 61) [1]				•																		SC
Kersten (2011, p. 16) [1]								•														SC
Leeuw, Grotenhuis and Goor (2013, pp. 969-970) [2]	•		•																			SC
Haumann *et al.* (2012, pp. 108-111) [2]	•			•																		R
Seifert *et al.* (2013, pp. 648-652) [2]	•			•																		R
Brosch *et al.* (2011a, pp. 856-857) [1]				•											•							VC
Brosch *et al.* (2012, p. 127) [2]	•			•	•										•							VC
Total:	10	3	3	9	1	1	1	8	1	2	1	1	1	1	2	1	3	1	2	1	1	

According to Table 10, 14 different authors use approaches based on questioning for identification and classification of complexity drivers. These approaches are applied to gather the expert's knowledge and experience. Further methods for identification of complexity drivers are the process or situation observation, the process analysis and the activity-based costing. They are used by 11 different authors. During a process analysis, the process is divided into its parts to increase process' understanding and to identify the main parts, as well as possible weaknesses. Activity-based costing is based on the process analysis. The costs are divided into direct and indirect costs to identify cost drivers and thus complexity drivers. Another possibility to identify complexity drivers is to analyze a company's system or structure. During a system analysis, the system is divided into its parts with the objective of identification and analyzing system's behavior and the interdependency between the different parts (Krause, Franke and Gausemeier, 2007, pp. 16-19). The structure analysis is conducted in the same way as a system or a process analysis. To analyze the interdependency between the elements of processes, systems, parts or structures and to identify furthermore the specific complexity drivers, the following approaches are used in literature: Influence analysis, dependence analysis, cause-effect-analysis, variant mode and effect analysis, as well as failure mode and effect analysis. These approaches are based on a process, system or structure analysis. A further method to get an overview about a company's complexity and its drivers is to analyze the scientific literature or the existing documents in the company, as well as complexity diaries. Complexity diaries are used by the management and employees to document all causes of complexity in the company (Collinson and Jay, 2012, p. 42). In the existing literature, 4 authors use these approaches for identifying complexity drivers. ABC-analysis is also applied for identification of complexity drivers. Wildemann (1999a, p. 65) uses an ABC-analysis in combination with a system analysis in the field procurement and logistics. As a result of this analysis, the goods or components, which occur at any rate, but have the highest complexity in the system, are the complexity drivers. Other approaches for identification of complexity drivers are the factor analysis, the cost-benefit analysis and creativity techniques. The factor analysis is a multivariate statistical method used to describe variability based on an empirical research. The objective is to concentrate the high number of variables to a lower number, called factors. These factors are the main determining components in a system (Brosius, 2013, p. 789) and thus the complexity drivers. In literature, the cost-benefit analysis is also used to identify complexity drivers according to a company's performance. As a result of a cost-benefit analysis, the objects with the highest costs and lowest benefit can be identified as the complexity drivers (Vizjak and Schiffers, 1996, p. 9). The creativity techniques in combination with other approaches are also used for complexity driver's identification, but no specific creativity method is referred to in literature.

3.3.3.2 Operationalization and visualization of complexity drivers

After identification of complexity drivers, the next step for a target-oriented complexity management is to operationalize and visualize the complexity drivers. Based on the literature analysis, 17 authors and 8 different approaches were identified for operationalization of complexity drivers. For visualization of complexity drivers, 19 authors and 8 approaches were found. The most applied approach in both areas is the classification- and driver-matrix. Table 11 presents an overview of the identified approaches and the fields. Some authors combine different approaches to operationalize complexity drivers.

The identified approaches for operationalization and visualization were also clustered into 7 fields based on their principle to increase transparency and understanding. Again, this is just a mere reflection of the approaches found in literature without an evaluation of their application in practice. However, it can be seen that some approaches, like the classification- and driver-matrix and the cluster analysis, are used for both, visualization and operationalization. Further research may include the evaluation of the application of different approaches in practice and their precise fields of application. Because some approaches are used for both, visualization and operationalization, it is not clear, how these approaches are used and clarification through further research is needed.

Table 11: Overview of approaches for operationalization and visualization of complexity drivers in particular fields (Part A)

Explanation according to focus:

- G General in manufacturing companies
- PD Product Development*
- PC Procurement/Purchasing*
- L Logistics
- PR Production*
- OPD Order Processing/Distribution/Sale*
- SC Internal Supply Chain
- R Remanufacturing
- VC Total Value Chain

* No approaches for operationalization or visualization of complexity drivers were found in this field.

Language of literature source:

- [1] German (Number: 18)
- [2] English (Number: 4)

Approach(es) based on...

1: Classification; 2: Influence & Dependency; 3: Questioning; 4: System; 5: Structure; 6: Evaluation; 7: Others

	Operationalization									Visualization								
	1		2	3	4	6	7			1			2	5			6	
Author(s)	Classification-/Driver-Matrix	Cluster Analysis	Influence Analysis	Expert Interviews	System Analysis	Scoring Methods	Factor Analysis	Portfolio Methods		Classification-/Driver-Matrix	Complexity Vector	Cluster Analysis	Cause-Effect-Diagram (Ishikawa)	Variant Tree/Complexity Tree	Descriptive Model	Swimlane-Diagram	Radar Chart	Focus
Stark and Oman (1995, pp. 428-430) [2]						•											•	G
Puhl (1999, pp. 55-57, 69-71) [1]			•							•								G
Purle (2004, pp. 109-111) [1]		•								No approach referred								G
Größler, Grübner and Milling (2006, pp. 261-264) [2]							•			No approach referred								G
Schuh, Sauer and Döring (2006, pp. 73-74) [1]	No approach referred														•			G
Meyer (2007, pp. 118-123) [1]	•				•					•								G
Dalhöfer (2009, pp. 71-76) [1]			•	•						No approach referred								G
Lasch and Gießmann (2009b, p. 117) [1]		•	•			•		•				•						G
Schawel and Billing (2011, p. 111) [1]	•									•								G
Schuh *et al.* (2011, pp. 118-119) [1]	No approach referred													•				G
Schuh *et al.* (2014a, pp. 314-315) [1]	No approach referred													•				G

Table 11: Overview of approaches for operationalization and visualization of complexity drivers in particular fields (Part B)

Explanation according to focus:

G	General in manufacturing companies
PD	Product Development*
PC	Procurement/Purchasing*
L	Logistics
PR	Production*
OPD	Order Processing/Distribution/Sale*
SC	Internal Supply Chain
R	Remanufacturing
VC	Total Value Chain
*	No approaches for operationalization or visualization of complexity drivers were found in this field.

Language of literature source:

[1] German (Number: 18)
[2] English (Number: 4)

Approach(es) based on...

1: Classification
2: Influence & Dependency
3: Questioning
4: System
5: Structure
6: Evaluation
7: Others

Author(s)	Operationalization									Visualization								Focus
	1		2	3	4	6	7			1			2	5			6	
	Classification-/Driver-Matrix	Cluster Analysis	Influence Analysis	Expert Interviews	System Analysis	Scoring Methods	Factor Analysis	Portfolio Methods		Classification-/Driver-Matrix	Complexity Vector	Cluster Analysis	Cause-Effect-Diagram (Ishikawa)	Variant Tree/Complexity Tree	Descriptive Model	Swimlane-Diagram	Radar Chart	Focus
Krizanits (2015, pp. 44-46) [1]	No approach referred																•	G
Haumann *et al.* (2012, pp. 108-111) [1]	•												•					G, R
Lammers (2012, pp. 32-35) [1]	•	•									•							G
Steinhilper *et al.* (2012, pp. 361-364) [1]	•												•					G, R
Aelker, Bauernhansl and Ehm (2013, p. 81) [2]	•									•								G
Seifert *et al.* (2013, pp. 648-652) [2]	•												•					G, R
Wildemann and Voigt (2011, pp. 116-117) [1]														•				G
Lasch and Gießmann (2009a, pp. 223-227) [1]	•		•			•				•								L
Kersten, Lammers and Skirde (2012, pp. 22-31) [1]	•	•									•							L
Kersten (2011, p. 17) [1]	•									•								SC
Brosch *et al.* (2011b, pp. 73-74) [1]	•															•		VC
Total:	11	4	4	1	1	3	1	1		6	2	1	3	3	1	1	2	

The most applied approach in scientific literature for operationalization and visualization of complexity drivers is the classification- or driver-matrix. Here, the complexity drivers are grouped and evaluated according to their influences, dependencies and effects. Based on the evaluation results, complexity drivers can be visualized in a portfolio-diagram to identify critical complexity drivers.

To identify and operationalize the influences, dependencies and effects of complexity drivers, some authors use an influence or system analysis. Based on an influence or system analysis, further methods for visualization of complexity drivers in the field of classification are the complexity vector and the cause-effect diagram, named Ishikawa-diagram. Compared to Ishikawa, the complexity vector is more complex and difficult. Generating complexity vectors, Kersten, Lammers and Skirde (2012, pp. 22-32) classify complexity drivers in the 2 dimensions micro and macro based on their system's influence and the results of a cluster analysis. In this case, the cluster analysis is applied to operationalize and classify the complexity drivers in related groups to increase transparency. Further methods for operationalization of complexity drivers are expert interviews, factor analysis, scoring methods and portfolio methods.

Based on a system's structure, 3 different approaches for visualization of complexity drivers are applied: Descriptive model, variant tree and swimlane-diagram. The descriptive model is used to describe a system's complexity, whereby the drivers can be visualized. With variant trees and swimlane-diagrams, the complexity drivers can be organized in a hierarchical structure. Based on the evaluation of complexity drivers using scoring methods, the radar chart can also be applied for visualization of complexity drivers in an easy way.

3.3.4 Complexity drivers in manufacturing companies and along the value chain

As already mentioned, complexity drivers have an influence on companies and the total value chain (Schuh, 2005, pp. 8-19). According to the origin, complexity can be separated in internal and external parts (Blecker, Kersten and Meyer, 2005, pp. 48-51; Kersten *et al.*, 2006, pp. 326, 337; Zahn, Kapmeier and Tilebein, 2006, pp. 142-143), called internal and external complexity drivers. Internal and external complexity drivers are connected directly and induce system's complexity (Größler, Grübner and Milling, 2006, p. 256; Grimm, Schuller and Wilhelmer, 2014, pp. 91-93; Belz and Schmitz, 2011, pp. 185-186; Collinson and Jay, 2012, pp. 7-8; Götzfried, 2013, pp. 35-38, 67-68). Consequently, internal and external complexity drivers cannot be separated selectively and operationalized (Schmidt, 1992, p. 14; Bohne, 1998, pp. 58-59; Schuh and Schwenk, 2001, pp. 10-13; Götzfried, 2013, pp. 67-68).

Bliss (1998, pp. 147-148; 2000, pp. 4-7, 65-66, 163-169) follows the categorization of internal and external complexity drivers in principle, but he extends the idea and differentiates internal complexity drivers in correlated and autonomous complexity drivers. Correlated complexity drivers have a direct correlation to the external market's complexity and are influenced by it. Autonomous complexity drivers are not influenced by external factors. They are determined by the company itself. In literature, 15 authors apply the differentiation of Bliss in their publications (see appendix Table 46). Furthermore, Curran, Elliger and Rüdiger (2008, p. 162) conclude that it is required to separate the complexity drivers in value adding and non-value adding drivers. Mahmood, Rosdi and Muhamed (2014, p. 1851) argue that "in measuring cost of complexity, the decision is to find the complexity driver that invested more cost, but does not contribute much to customer's buying decision".

3.3.4.1 Internal complexity drivers

Internal complexity drivers describe the company's complexity and can be influenced actively by the company itself (Picot and Freudenberg, 1998, pp. 70-71; Wildemann, 1998, pp. 47-52; Bliss, 2000, pp. 4-7; Kersten, Koppenhagen and Meyer, 2004, p. 211; Purle, 2004, pp. 109-113; Kersten *et al.*, 2006, pp. 326, 337; Kersten, 2011, p. 16; Binckebanck and Lange, 2013, p. 100; Boyksen and Kotlik, 2013, p. 48; Aelker, Bauernhansl and Ehm, 2013, p. 81). They occur as a result of external complexity drivers or are induced by the company itself (Heina, 1999, pp. 10-17; Wegehaupt, 2004, pp. 38-39; Hanenkamp, 2004, pp. 2-3; Greitemeyer and Ulrich, 2005, p. 2; Rudzio, Apitz and Denkena, 2006, pp. 52-53; Collinson and Jay, 2012, pp. 7-9; Lammers, 2012, pp. 31-35). Götzfried (2013, p. 37) argues that internal complexity is a translation of external complexity, which is induced exclusively by the company. Wildemann (1995, p. 22) separates internal complexity drivers in 3 categories: Structural, informational and individual complexity drivers.

3.3.4.2 External complexity drivers

External complexity drivers are factors, which influence the company's complexity directly from outside (Höge, 1995, pp. 16-17; Wildemann, 1995, p. 22; Wildemann, 1998, pp. 47-52; Heina, 1999, pp. 10-17; Klepsch, 2004, pp. 7-9; Kersten, Koppenhagen and Meyer, 2004, p. 211; Purle, 2004, pp. 114-117; Kersten *et al.*, 2006, pp. 326, 337; Piller, 2006, p. 54; Gießmann and Lasch, 2011, pp. 4-6; Kersten, 2011, p. 16; Collinson and Jay, 2012, pp. 30-32; Binckebanck and Lange, 2013, pp. 99-100; Aelker, Bauernhansl and Ehm, 2013, p. 81). Bohne (1998, pp. 58-59) and Klepsch (2004, pp. 7-9) describe that external complexity produces internal complexity as a reaction. Piller (2006, p. 130) defines external complexity as a "mirror picture" of the market's requirements. Normally, external complexity drivers are constant and cannot or nearly cannot be influenced by the company itself, because they are not induced by the company (Picot and Freudenberg, 1998, pp. 70-71; Biersack, 2002, p. 54; Wegehaupt, 2004, pp. 38-39; Kersten *et al.*, 2006, pp. 326, 337; Gießmann and Lasch, 2011, pp. 4-6; Kersten, 2011, p. 16; Lammers, 2012, pp. 31-35; Binckebanck and Lange, 2013, pp. 99-100; Boyksen and Kotlik, 2013, p. 48; Götzfried, 2013, pp. 35-38, 67-68).

To handle external complexity, companies typically respond with an unwanted increase of internal and accordingly non-value adding complexity (Wildemann, 1999b, pp. 31-32; Dehnen, 2004, pp. 32-33; Greitemeyer and Ulrich, 2005, p. 2; Piller, 2006, p. 130; Greitemeyer, Meier and Ulrich, 2008, pp. 37-38; Belz and Schmitz, 2011, pp. 193-194; Collinson and Jay, 2012, p. 7). Größler, Grübner and Milling (2006, p. 256) argue that external complexity drivers force the company to build up internal complexity.

3.3.4.3 Complexity driver's classification system

Managing complexity in companies requires the identification of complexity sources. Lasch and Gießmann (2009a, p. 200) describe that the complexity sources and their effects are various. Thus, a complete list of all sources cannot be specified. In literature, more than 480 different complexity drivers were found during our research in 223 literature parts concerning complexity drivers in manufacturing companies and along the value chain. For a better understanding and overview, Schöttl *et al.* (2014, p. 259) suggest that complexity drivers "have to be aggregated to a small, abstract and well-defined collection". To increase transparency, Klagge and Blank (2012, pp. 6-7), Wildemann (1998, p. 48), Lasch and Gießmann (2009a, pp. 200-202; 2009b, p. 116) and Gießmann (2010, pp. 36-38) follow this approach and also separate their identified complexity drivers in different clusters according to their origin, characteristics and influences on other drivers. The framework for the classification system, used in this research, is based on existing classification systems in literature provided by different authors. To create a superior classification system without overlaps between the different complexity driver categories, we analyzed and synthesized the existing systems as follows:

In their research, Bliss (1998, pp. 147-148; 2000, pp. 4-7, 65-66, 163-169), Kirchhof (2003, pp. 39-41), Hasenpusch, Moos and Schwellbach (2004, p. 135), Keuper (2004, p. 83), Marti (2007, pp. 14-17), Mayer (2007, pp. 23-29), Lasch and Gießmann (2009a, pp. 200-202), Gießmann (2010, pp. 36-38), Gießmann and Lasch (2011, pp. 4-6), Schömann (2012, pp. 135-138), Götzfried (2013, pp. 35-38), Schoeneberg (2014a, pp. 16-19), Grimm, Schuller and Wilhelmer (2014, p. 93) and Lammers (2012, pp. 31-35) cluster complexity drivers according to their origin into external and internal drivers. Furthermore, they separate the internal drivers into internal correlated and internal autonomous complexity drivers. Schubert (2008, p. 134) argues that external complexity comprises complexity drivers from a market-based view and internal complexity comprises drivers from a resource-based view.

In our study, we followed the already mentioned classification and divide our classification system into the 2 main categories: Internal and external complexity drivers. Further, we also divided the internal complexity drivers in internal correlated and internal autonomous complexity drivers (see Figure 8).

In literature, Keuper (2004, p. 83), Marti (2007, pp. 14-17), Lasch and Gießmann (2009a, p. 201), Gießmann (2010, p. 38), Gießmann and Lasch (2011, p. 5), Schoeneberg (2014a, p. 17), Grimm, Schuller and Wilhelmer (2014, p. 93) and Ruppert (2007, pp. 68-70) subdivide external complexity into society complexity and market complexity. Society complexity is determined by cultural factors (language, working hours, habit, working method and education), ecological factors, legal factors, standards and regulations and political factors. The list with all identified complexity drivers in this and all other categories, which will be mentioned, is shown in the appendix (see Table 47). Asan (2009, p. 37) and Serdarasan (2011, p. 794) use the term geopolitical complexity synonymously for society complexity. However, in literature most of the authors use the term society complexity, which is the reason, why we followed this nomenclature. In literature, market complexity is further subdivided in different subcategories. Keuper (2004, p. 83), Lasch and Gießmann (2009a, p. 201), Gießmann (2010, p. 38), Gießmann and Lasch (2011, p. 5), Schoeneberg (2014a, p. 17), Grimm, Schuller and Wilhelmer (2014, p. 93) assign the subcategories demand complexity, competitive complexity and supply complexity to this subcategory. Bliss (1998, p. 147; 2000, pp. 4-7), Marti (2007, pp. 14-17), Schömann (2012, p. 136) and Blockus (2010, pp. 16-17) follow this assignment and extend the subcategory by adding technological complexity (external). In literature, we found several single market-related complexity drivers, which cannot be assigned to the previously mentioned categories. Thus, we introduced a new category, called general market-related complexity.

As already mentioned, in our research, we divided the main category internal complexity into the subcategories internal correlated and internal autonomous complexity. Bliss (2000, pp. 4-7, 65-66, 163-169), Lasch and Gießmann (2009a, pp. 200-202), Gießmann (2010, p. 38), Gießmann and Lasch (2011, p. 5), Schömann (2012, p. 137) and Marti (2007, pp. 14-17) assign the following complexity driver categories to the subcategory internal correlated complexity: Target complexity, customer complexity, as well as product and product portfolio complexity. Keuper (2004, p. 83), Schoeneberg (2014a, p. 17) and Grimm, Schuller and Wilhelmer (2014, p. 93) follow this assignment and extend the subcategory by adding technological complexity (internal). Other authors have added further complexity driver categories to the subcategory internal correlated complexity. However, these categories could not be allocated to the existing categories. Thus, they became independent categories within the subcategory internal correlated complexity. Bayer (2010, p. 17), Dehnen (2004, pp. 32-35), Kim and Wilemon (2003, p. 20) and Wildemann and Voigt (2011, p. 70) add the category product development complexity and Bayer (2010, p. 17), Blockus (2010, pp. 16-22) and Nurcahya (2009, p. 29) add the category supply process complexity to the mentioned subcategory. The subcategory internal correlated complexity is completed by adding the categories service complexity and remanufacturing complexity. Service complexity is added by Schmidt (2009, pp. 91-92), Collinson and Jay (2012, p. 32) and Dalhöfer (2009, p. 25). Remanufacturing complexity is added by Bayer (2010, p. 17), Haumann *et al.* (2012, pp. 107-108, 111), Steinhilper *et al.* (2012, pp. 360-361, 364), Seifert *et al.* (2013, p. 650) and Butzer *et al.* (2014, pp. 366-369). In summary, the subcategory internal correlated complexity comprises 8 complexity driver categories: Target complexity, customer complexity, product and product portfolio complexity, technological complexity (internal), product development complexity, supply process complexity, service complexity and remanufacturing complexity.

In the next step, the subcategory internal autonomous complexity is defined. Lasch and Gießmann (2009a, p. 201), Gießmann (2010, p. 38), Gießmann and Lasch (2011, p. 5), Schoeneberg (2014a, p. 17), Grimm, Schuller and Wilhelmer (2014, p. 93) and Schömann (2012, pp. 137-138) assign the categories organizational complexity and process complexity to the subcategory internal autonomous complexity. Lasch and Gießmann (2009a, p. 201), Gießmann (2010, p. 38), Gießmann and Lasch (2011, p. 5) and Schoeneberg (2014a, p. 17) extend the subcategory by the category structure complexity. However, several authors, such as Asan (2009, p. 37), Serdarasan (2011, p. 794), Reiß (1993a, pp. 3, 9), Blockus (2010, pp. 16-22), Wildemann and Voigt (2011, p. 70), Höge (1995, p. 6), Blecker, Kersten and Meyer (2005, p. 49), Kersten *et al.* (2006, p. 328), Schubert (2008, pp. 134-136), Collinson and Jay (2012, pp. 31-32), Schuh, Gartzen and Wagner (2015, p. 4), Götzfried (2013, pp. 35-38), Ruppert (2007, p. 69), Schulte (1995, pp. 758-761), Lindemann, Maurer and Braun (2009, p. 27) and Größler, Grübner and Milling (2006, p. 257) include structural complexity drivers in the category organizational complexity. To avoid overlaps in our classification system, we also assigned structural complexity drivers to the category organizational complexity. Other important categories, which are added to the subcategory internal autonomous complexity are the categories production complexity and planning, control and information complexity. In literature, production complexity is defined by Bliss (1998, pp. 147-148; 2000, pp. 4-7), Bayer (2010, p. 17), Mayer (2007, p. 24), Keuper (2004, pp. 84-85), Gießmann and Lasch (2011, p. 5), Lasch and Gießmann (2009a, p. 201), Schömann (2012, pp. 137-138), Blockus (2010, pp. 16-22), Marti (2007, pp. 14-17), Klepsch (2004, p. 8), Pepels (2003, p. 551), Ruppert (2007, p. 69), Gronau and Lindemann (2009, pp. 21-22), Westphal (2000, p. 19), Jäger *et al.* (2013, p. 341), Götzfried (2013, pp. 35-38), Schulte (1992, pp. 84-86) and Schmidt (2009, pp. 91-92). The category planning, control and information complexity is defined by Keuper (2004, p. 86), Mayer (2007, p. 24), Gießmann and Lasch (2011, p. 5), Lasch and Gießmann (2009a, p. 201), Schömann (2012, pp. 137-138), Schoeneberg (2014a, p. 17), Ruppert (2007, p. 69), Klagge and Blank (2012, pp. 6-7), Jäger *et al.* (2013, p. 341), Gullander *et al.* (2011, p. 4), Grimm, Schuller and Wilhelmer (2014, p. 93) and Herrmann (2010, p. 79). Furthermore, the categories resource complexity, defined by Höge (1995, p. 6), Reiners and Sasse (1999, pp. 222, 224) and Bohne (1998, p. 61), logistics complexity, defined by Klagge and Blank (2012, pp. 6-7), and sales and distribution complexity, defined by Bayer (2010, p. 17) and Klepsch (2004, p. 8), are added to the subcategory internal autonomous complexity. In total, the subcategory internal autonomous complexity comprises 7 complexity driver categories: Organizational complexity, process complexity, production complexity, planning, control and information complexity, resource complexity, logistics complexity and sales and distribution complexity.

As already mentioned, complexity drivers are separated according to their origin into external and internal complexity drivers. In literature, a further superior classification system exists. Denk and Pfneissl (2009, p. 21) separate the complexity drivers in 2 main groups: General complexity drivers (e.g. transparency, uncertainty, etc.) and precise complexity drivers (e.g. organizational complexity, process complexity, technological complexity etc.). General complexity drivers are also referred to by Mayer (2007, pp. 23-29), Reiß (1993a, pp. 3, 9; 1993b, p. 54), Berens and Schmitting (1998, p. 98), Herrmann (2010, p. 79), Gronau and Lindemann (2009, p. 22), Kolbusa (2013a, pp. 85-86; 2013b, pp. 89-92), Schmitt, Vorspel-Rüter and Wienholdt (2010, pp. 843-844), Kersten *et al.* (2006, p. 328), Blecker, Kersten and Meyer (2005, p. 49), Bick and Drexl-Wittbecker (2008, pp. 30-31) and Waldthausen (2007, pp. 4-5). Thus, we included a third main complexity category, called general complexity in our classification system. The total classification system is shown in Figure 8.

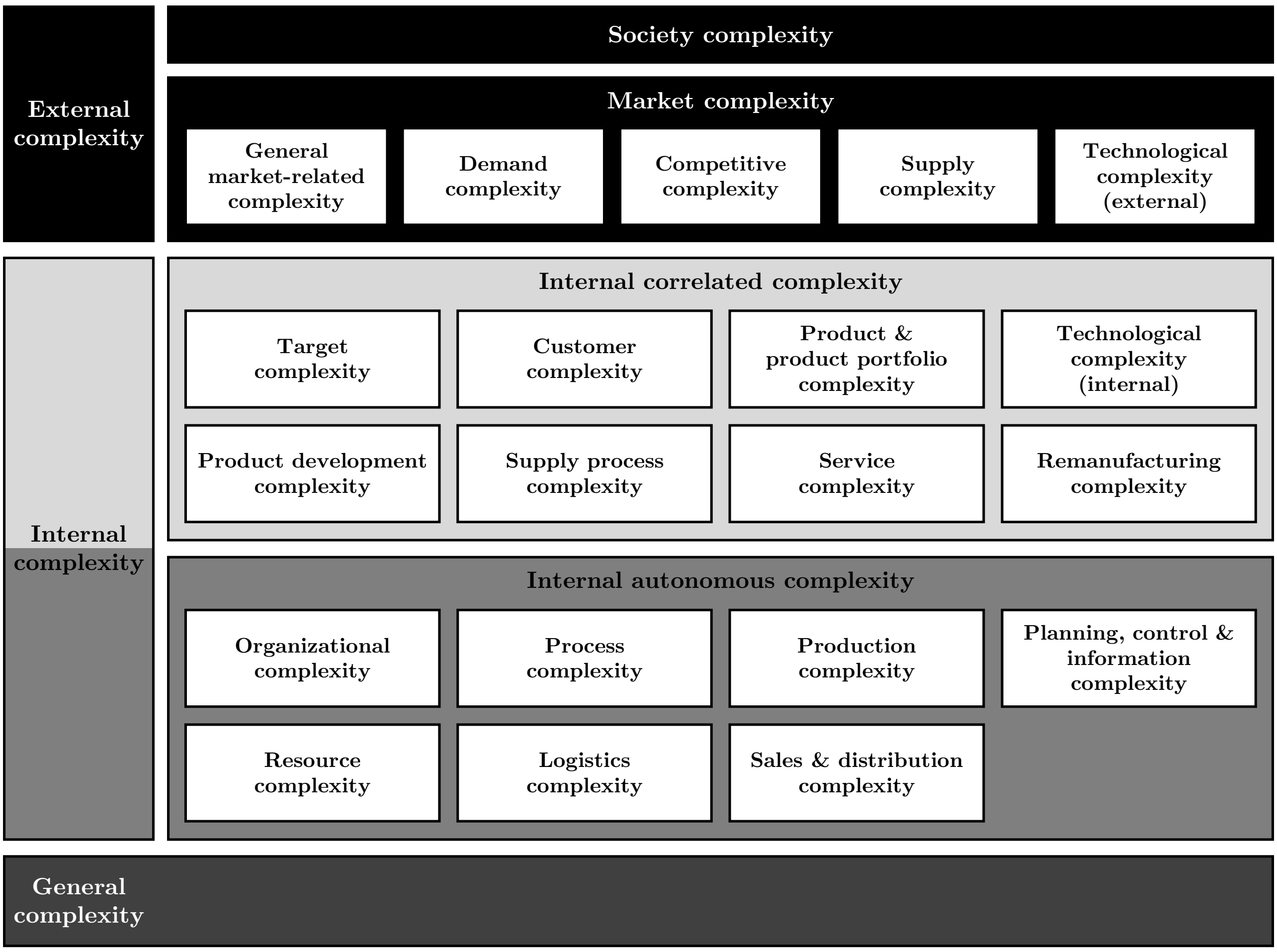


Figure 8: Complexity driver's classification system

After defining the superior complexity driver classification system, we assigned the complexity drivers, found in literature, to these previously defined main groups and categories. According to literature, we clustered the identified complexity drivers (more than 480) as follows:

- **3 main groups** (external complexity, internal complexity and general complexity)
- **4 subcategories** (society complexity, market complexity, internal correlated complexity and internal autonomous complexity) and
- **22 main complexity driver categories** (society, general market-related, demand, competitive, supply, technological external, target, customer, product & product portfolio, technological internal, product development, supply process, service, remanufacturing, organizational, process, production, planning, control & information, resource, logistics, sales & distribution, general complexity), depending on their origin, characteristics and influences on other drivers. The subcategory society complexity and the main group general complexity are also added to the 22 main complexity driver categories, because they cannot be further subdivided into different driver categories. Thus, we added the identified single complexity drivers directly to these 2 categories.

For complexity driver's clustering, we analyzed all identified drivers and summarized them according to their context and similarities in a superior complexity driver category. As already mentioned, this framework is based on literature. For example, in the category 'society complexity', we identified the following 7 single complexity drivers and aggregated them to the mentioned superior category: Social framework, social requirements, social change, social behavior, cultural framework, cultural factors (language, working hours, habit, working method, education) and cultural differences. In the category 'technological complexity (external)', we identified the following 9 single complexity drivers, which were also aggregated to the mentioned superior category: Technological progress, technological change, different technological standards, technological innovations, technological intensity, technological dynamics, new technologies and materials, combination of different technologies and technology integration. In the main group 'general complexity', we aggregated all complexity drivers, which cannot be assigned to the other 2 main groups and 4 subcategories. In the main group 'general complexity', we assigned 28 single complexity drivers, such as stability, instability, perception, time, costs, quality, flexibility, cost effectiveness, transparency etc. For the other complexity driver categories, we performed the clustering process analogously. Figure 9 presents the clustered 22 main complexity driver categories and their occurrence in literature in all fields (general in manufacturing companies and along the value chain). Table 47 in the appendix shows the different complexity drivers in each category and group.

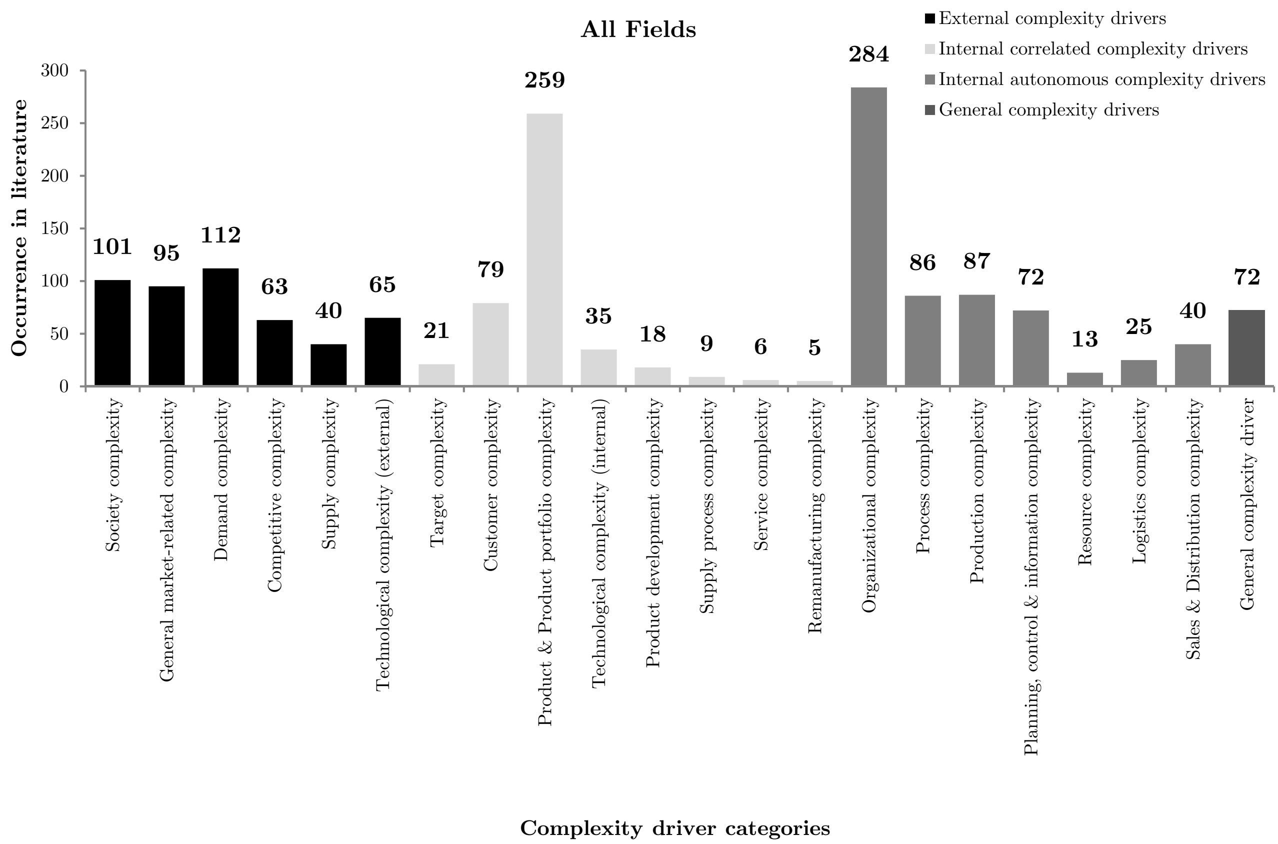


Figure 9: Overview about complexity driver's clustering and their occurrence in literature

To answer the third research question, we separated the data from Figure 9 into the different fields 'general in manufacturing companies' and 'along the value chain'. As a result of Table 12, some fields are influenced by more complexity drivers than other fields. The amount of complexity drivers in a system reflects the level of difficulty in managing a system's complexity, because complexity drivers have a high influence on a system's complexity. Complexity drivers are strictly connected with their category. For a target-oriented complexity management, it is necessary to handle all complexity drivers in a certain category of a specific system. Overall, it can be summarized that system's complexity is influenced by the complexity driver categories. For example, the field production is influenced by 15 complexity driver categories while remanufacturing is influenced by 7 complexity driver categories. Thus, the implementation of a target-oriented complexity management in the field production is more difficult than in the field remanufacturing, because more complexity sources must be considered.

Table 12: Overview of the main complexity drivers in particular fields and complexity driver's literature occurrence

Origin	Complexity driver category [N: 22]	Number of specific complexity drivers	**RQ3**: Fields									Total literature occurrence in all fields
			General in manufacturing companies	Value Chain								
				Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	
External complexity	Society 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 & 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 & 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 & Distribution complexity	**40**	18	3	0	3	1	9	4	0	2	**40**
General	General complexity	**28**	48	1	4	2	8	0	7	1	1	**72**
Total amount of complexity driver's literature occurrence		**486**	**824**	**94**	**36**	**147**	**140**	**124**	**168**	**32**	**23**	
Influenced by... complexity driver categories			**22**	**18**	**15**	**19**	**19**	**20**	**18**	**9**	**10**	

As also seen in Table 12, market complexity, product and product portfolio complexity and organizational complexity are complexity driver categories that influence all fields in manufacturing companies. Thus, these categories are the most important in the company and must be managed first for a target-oriented complexity management. Another important category, which has an influence on many fields in the company, is society complexity. This category must also be managed for a target-oriented complexity management. Furthermore, all fields are influenced by internal and external complexity driver categories. However, the different fields are mostly influenced by internal driver categories, which can be influenced actively by the company itself. When investigating the different fields, it can be seen that the fields general in manufacturing companies, logistics, production, order processing/distribution/sale and internal supply chain are mostly influenced by internal autonomous complexity driver categories. Internal autonomous complexity driver categories are not influenced by external factors and are determined by the company itself. In contrast, the field remanufacturing is influenced mostly by internal correlated complexity driver categories. The internal correlated complexity driver categories have a direct correlation to company's environment (e.g. market and society) and are influenced by it. The fields product development, procurement/purchasing and general in value chain are influenced almost to the same extend by internal correlated, as well as internal autonomous complexity driver categories.

In the next step, we tried to identify the main complexity driver categories in the referred fields. In literature, the following approaches are applied to identify the most important factors among many factors: Factor analysis (Backhaus *et al.*, 2011, pp. 330-335; Brosius, 2013, p. 789), factor screening (Kleijnen, 2009, pp. 153-162), DoE - design of experiments (Siebertz, Bebber and Hochkirchen, 2010) and Pareto-analysis (Kirsch, 2009, p. 218). The factor analysis is a statistical method and used for data reduction in empirical researches or experiments. The aim is to get a small set of variables from a large set of variables to identify the most important factors (Backhaus *et al.*, 2011, pp. 330-335; Brosius, 2013, p. 789). Kleijnen (2009, p. 153) uses the factor screening method in simulation experiments to identify the most important factors. "Factor screening [...] means that the analysts are searching for the most important factors among the many factors that can be varied in their experiment" (Kleijnen, 2009, p. 153). For screening, Kleijnen (2009, pp. 155-157) uses different screening designs to treat the simulation model as a black box. Another method to identify variables, which have the most influence on other variables or parameters in an experiment, is the design of experiments (DoE). The DoE is normally used for the development and optimization of products and processes (Siebertz, Bebber and Hochkirchen, 2010). Another approach for identification and separation of the most important factors among many factors is the Pareto-analysis. The Pareto-principle describes that 80% of the effects come from 20% of the causes (Kirsch, 2009, p. 218). All of the mentioned principles can be used to identify the most important factors, variables or inputs. However, none of these approaches were applicable to identify the main complexity driver categories in our opinion. The approaches factor analysis, factor screening and design of experiments are based on experiments, whereas the Pareto-principle can be used more generally without experiments. The Pareto-principle is based on causes and effects. Transferred to our research, the cause would be the number of a complexity driver's categories appearance in literature and the effect would be the importance of the specific category. Since it would be naive to derive the importance of a specific complexity driver's category from its number of appearances in literature, this principle also was not applicable. Further research is necessary to identify an approach for analyzing and identifying important complexity driver categories.

3.4 Conclusion and outlook

Before starting our research, we reviewed the literature and searched for existing literature studies about complexity drivers and gaps in literature. As a result of our literature search, we identified 4 literature studies about complexity drivers, which have been done by Meyer (2007, pp. 182-183), Serdarasan (2011, pp. 793-795; 2013, pp. 534-535) and Wildemann and Voigt (2011, pp. 44-52, 63-72, 113-170). After identification, the previous literature studies were analyzed and evaluated based on the following 11 criteria (see also Table 5): Type of literature study, focus, research period, amount of identified literature sources, complexity driver's definition, described complexity drivers and complexity driver's categories, determination of research questions, databases, search terms and synthesizing methods, comparison of literature findings with other literature sources or empirical research data.

The existing studies comprise several literature sources in the period between 1991 and 2011. However, a systematic, explicit and reproducible method for literature's identification, evaluation and synthesizing is not described. To describe the current state of knowledge in a particular field of research, it is essential to determine the research questions, databases, search terms, the synthesizing methods, as well as to compare the findings with other literature sources. Only Wildemann and Voigt (2011, pp. 44-52, 63-72) and Serdarasan (2013, pp. 534-535) compare their findings with the findings of other literature sources. Another important criteria for the scientific research is the specification of the different literature sources about complexity drivers, the trends in literature over the last years and the gaps in literature for future research. These requirements are not fulfilled in the previous literature studies. Furthermore, only the fields logistics, supply chain and general in manufacturing companies are described. In literature, an overview regarding complexity drivers general in manufacturing companies and in all parts along the value chain does not exist so far. Another deficit in the existing studies is that they present only 1 definition of complexity drivers. In our opinion, different definitions of complexity drivers should be analyzed, compared and discussed to identify all characteristics of complexity drivers. In the already mentioned studies, no approaches for identification and operationalization are described. Only 1 method for complexity driver's visualization is described by Wildemann and Voigt (2011, pp. 116-117). For the researcher, it is important to know, what a complexity driver is and what approaches can be applied for complexity driver's identification, operationalization and visualization. Our purpose is to provide an overview about different definitions and methods for complexity driver's identification, operationalization and visualization for closing these research gaps. In addition, we develop a new overall definition of complexity drivers to summarize all characteristics.

To provide this literature review and to fulfill all requirements, we used the methodology of Fink (2014, pp. 3-5). The research method is described in section 3.2. First, we started our research process by defining our research questions, which guide the literature review. The search term was defined by finding the lowest common denominator of the many different paraphrases of the term complexity driver that exist in literature. Then, we defined our databases. For our research, we defined our search terms in English and German to extend the results and to prevent the elimination of important articles. The literature search was performed in 8 English and German databases and resulted in 11.425 literature sources. For analyzing and synthesizing the literature, we followed the approach of the qualitative content analysis. The synthesizing process finally resulted in 235 relevant papers in the time period between 1991 and 2015. Before 1991, no relevant literature sources concerning the issue complexity drivers were found in our research. The reasons could be attributed to complexity management's evolution over the last 25 years and the principal definition and understanding of the term "complexity driver". Analyzing the overall trend of the literature regarding complexity drivers in manufacturing companies and along the value chain shows an increased interest throughout the last 10 years (see Figure 6). Between 2004 and 2015, 74% of all publications were published. More than 50% of all the publications about complexity drivers were published in journals and PhD theses. Thus, complexity drivers have a high importance in scientific research. In our research, we found out that 212 papers describe specific complexity drivers in manufacturing companies and along the value chain. After analyzing and synthesizing these papers, we identified 223 different literature parts concerned with complexity drivers in the 2 categories manufacturing companies (108 parts) and along the value chain (115 parts). In literature, 11 papers describe both parts. The trends of the 2 categories during the last 25 years show that there is an increasing interest in complexity drivers along the value chain in scientific literature in the last 10 years (see Figure 7). However, most publications with focus on general in manufacturing companies were published between the years 1998 and 2010. A comparison between these trends shows that complexity drivers are now described more in detail regarding different parts along the value chain. This indicates that complexity drivers gain more and more importance for scientific research. In the next step, the data from the category complexity drivers along the value chain was separated in the following 8 different fields and analyzed: Product Development (PD), Procurement/Purchasing (PC), Logistics (L), Production (PR), Order Processing/Distribution/Sale (OPD), Internal Supply Chain (SC), Remanufacturing (R) and General in Value Chain (VC). The analysis shows that the amount of publications about complexity drivers in all 8 different fields has increased over the last 10 years.

This chapter describes a variety of definitions and methods for identification, operationalization and visualization of complexity drivers. Within the last decades, complexity has increased continuously in many industries, caused by internal and external sources, called complexity drivers. Identifying, analyzing and understanding complexity drivers are the first steps in developing and implementing a clear strategy to handle complexity in the company. For an effective complexity management, it is necessary to know the key drivers of complexity in a system, because they are the main adjusting levers for company's success. Furthermore, managing a system's complexity requires an optimum fit between internal and external complexity. Thus, complexity drivers play a significant role for complexity management and are a strategic issue for companies to be competitive.

For this literature review, we determined 3 research questions, which were answered as follows. Before identification, it is necessary to understand, what a complexity driver is (Meyer, 2007, pp. 21-29; Kolbusa, 2013a, p. 83). To answer the first research question, the identified literature was analyzed and synthesized. The researched literature contains several different definitions of complexity drivers, defined by 36 authors. Based on their content, the definitions can be assigned to 5 main categories: Factors, indicators, sources, parameters/variables and symptoms/phenomenon. As a result, there is no universal understanding of the term "complexity driver", but the identified definitions tend towards similar definitions. To generate a general definition of complexity drivers, we analyzed the existing definitions by identifying their hypernyms and differentia. Several different hypernyms for the genus term complexity driver exist in literature, but we came to the conclusion that only the term factor covers the general understanding of a complexity driver in total. Then, the existing differentia, found in literature, were clustered into 5 groups based on their commonalities and differences. Based on the 5 groups of differentia and in combination with the hypernym term factor, we generated a more general definition of complexity driver.

A specific and target-oriented complexity management is based on identification, visualization and operationalization of system's complexity drivers. In literature, several different methods for identification, operationalization and visualization of complexity drivers are applied (see Table 10 and Table 11). Based on this literature review and to answer the second research question, 21 different approaches were identified in literature for complexity driver's identification, which were focused on different fields. The most applied approaches are expert interviews, process analysis and system analysis. We did not conduct an evaluation of all existing approaches regarding their practical uses. Our purpose was to reflect the different approaches, found in literature. We identified 8 different approaches for operationalization and visualization of complexity drivers in the existing literature. However, a clear assignment of the different approaches to operationalize and visualize complexity drivers was not possible in all cases. As a result, the most applied approach in both areas is the classification- and driver-matrix. Further research to eliminate this lack of definition is needed, as well as an evaluation of the existing approaches' practical application.

Complexity drivers have a direct influence on the company and the value chain. Complexity drivers can be separated in internal and external drivers, depending on their origin. Internal complexity drivers can also be differentiated in correlated and autonomous complexity drivers. In literature, more than 480 different internal and external complexity drivers were found during our research in 223 literature parts concerning complexity drivers in manufacturing companies and along the value chain. For clustering the 486 complexity drivers, we developed a superior classification system without overlaps between the different complexity driver categories based on existing classification systems in literature, provided by different authors. In summary, our new classification system consists of 3 main groups (external complexity, internal complexity and general complexity), 4 subcategories (society complexity, market complexity, internal correlated complexity and internal autonomous complexity) and 22 main complexity driver categories depending on their origin, characteristics and influences on other drivers (see Figure 8). The identified 486 complexity drivers were clustered into these complexity driver categories and groups. The assignment to the different categories and groups was done depending on complexity driver's origin, characteristics and influences on other drivers. Figure 9 presents an overview about the complexity driver categories and their occurrence in literature. The third research question was answered by means of analyzing the identified literature and synthesizing the complexity driver categories in the referred fields (see Table 12). The basis for synthesizing the categories can be found in Figure 8.

In summary, our new literature review covers complexity drivers in manufacturing companies and along the value chain over a period of 25 years (1991-2015). It fulfills all requirements in total (see Table 13) and closes the gap in literature.

Table 13: Evaluation of our new literature review about complexity drivers in comparison with existing literature studies

Author(s)		Meyer (2007, pp. 182-183)	Serdarasan (2011, pp. 793-795)	Wildemann and Voigt (2011, pp. 44-52, 63-72, 113-170)	Serdarasan (2013, pp. 534-535)	New Literature Review
Type of literature study		Overview	Review	Overview	Review	**Review**
Focus	General in manufacturing companies	•		•		•
	Product Development					•
	Procurement/Purchasing					•
	Logistics	•				•
	Production					•
	Order Processing/Distribution/Sale					•
	Internal Supply Chain		•		•	•
	Remanufacturing					•
	General in Value Chain					•
Research period		1992 - 2004	1998 - 2011	1991 - 2010	1992 - 2011	**1991 - 2015**
Literature review's results: Amount of ...	Identified literature sources	19	25	17	38	**235**
	Complexity driver's definitions	1	1	1	1	**18+1**
	Described complexity drivers	127	27	95	32	**486**
	Complexity driver categories	14	3	11	9	**22**
Determination of ... by the author(s)	Research questions	-	-	-	-	+ +
	databases	-	-	-	-	+ +
	Search terms	-	-	-	-	+ +
	Synthesizing methods	-	-	-	-	+ +
Literature findings' comparison with...	Other literature sources	-	-	+ +	+ +	+ +
	Empirical research data	-	-	+ +	-	**Future Research**

Evaluation criteria:

fulfilled (+ +) Precise research questions, databases, search terms and synthesizing methods are described. The literature findings are compared with other literature sources or empirical research data.

not fulfilled (-) Precise research questions, databases, search terms and synthesizing methods are not described. The literature findings are not compared with other literature sources or empirical research data.

In total, 235 literature sources are identified and more than 480 complexity drivers are described and clustered in 39 categories. The research method, including the research questions, databases, search terms and synthesizing methods, as well as the results and the trends of complexity drivers in literature and in the different fields over the last 25 years are also described. We compare our results with the findings of previously published literature. Gaps for future research are pointed out.

Furthermore, a new definition of the term "complexity driver" is specified based on the existing definitions by identifying a general hypernym and clustering existing differentia. Different methods that are applied in literature for complexity driver's identification, evaluation and visualization are described and give the reader a general overview. A new classification system was developed and the complexity driver categories and their complexity drivers general in manufacturing companies and along the value chain are pointed out (see appendix Table 47).

The review was focused only on the manufacturing industry. Future research may also include other sectors or industries, such as financing and/or insurance. It would also be interesting to compare the research results from other sectors with the results of this research. In addition, the findings of this chapter should be evaluated regarding their impact and relevance on practice by an empirical research analogously to the empirical research done by Wildemann and Voigt (2011, pp. 113-170). Further, the different approaches for complexity driver's identification, operationalization and visualization should be evaluated by the practice within an empirical research according to the following 3 categories: Amount of work, data volume and level of difficulty. Also, the different approaches should be evaluated regarding their specific fields of application. This information could encourage the user to find the right approach for his/her specific field of interest. Further research may also include finding an approach to identify and analyze the most important complexity driver's categories. As already mentioned, further research will be needed to create helpful advice for practitioners to detect complexity issues and to present methodological support to detect complexity causes and their effects.

4 Complexity drivers in product development: A comparison between literature and empirical research

4.1 Introduction

"I think the next (21st) century will be the century of complexity" (Hawking, 2000, p. 29). This statement by Stephen W. Hawking (2000, p. 29) from the year 2000 describes the current situation in science and practice. Maguire, Allen and McKelvey (2011, p. 1) describe that "complexity is one of the fastest growing topics" in scientific research. In practice, the same situation can be observed. Complexity in manufacturing companies and especially in product development has continuously increased in many industries within the last years (ElMaraghy *et al.*, 2012, pp. 793-797; Krause, Franke and Gausemeier, 2007, pp. 3-4; Lübke, 2007, pp. 2-4; Wildemann, 2005, p. 34; Schuh, Arnoscht and Rudolf, 2010, p. 1928). The reasons are social, market-specific, technological and economical changes, such as more and more demanding customers, market's globalization, dynamic market environment, technology innovations and uncertainty. Manufacturing companies have to face these trends and cannot escape (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Mohr, Sengupta and Slater, 2010, pp. 1-5, 9-21; Perona and Miragliotta, 2004, p. 103; Voigt *et al.*, 2011, p. 1). Increasing global competition and customer's individual needs force companies to offer a diversified product portfolio in the market, by developing different product variants (Anderson, 2006, pp. 1-26; Caridi, Pero and Sianesi, 2009, pp. 381-382; ElMaraghy and ElMaraghy, 2014, pp. 1-2; Haumann *et al.*, 2012, pp. 107-108; Cimatti and Tani, 2009, p. 1229). A diversified product portfolio with many different product variants causes an increase in complexity (Brosch and Krause, 2011, p. 1), especially in products and in processes (Beinhocker, 2007, pp. 4-5). Other reasons for increasing complexity in product development are the increasing number of product launches in the market, shorter product lifecycles and customer's demands for new and innovative products (Caridi, Pero and Sianesi, 2009, p. 381). According to Schaefer (1999, p. 311) and Chapman and Hyland (2004, p. 553), product development and innovation are important key factors for business success. For company's strategy, product development became a central importance (Clark and Fujimoto, 1991, pp. 1-15; Davila, 2000, p. 383; Gupta and Wilemon, 1990, p. 24). Increasing complexity is one of the biggest tasks that manufacturing companies have to face and to handle today (ElMaraghy *et al.*, 2012, p. 793). According to Warnecke and Puhl (1997, pp. 359-362), company's complexity can only be managed if it is identified. Thus, complexity understanding becomes more and more important in manufacturing companies (Isik, 2010, p. 3683).

According to Warnecke (2010, p. 639), complexity can be seen as a phenomenon and evolutionary process, which is challenging, especially for science and engineering. Complexity is intensified through innovations in products and processes (Warnecke, 2010, p. 639). In scientific research, there is no general understanding, as well as an explicit, universal and widely accepted definition of the term "complexity" (Brosch and Krause, 2011, p. 2; ElMaraghy *et al.*, 2012, p. 794; Riedl, 2000, pp. 3-7). Complexity is "in the eye of the beholder" (Meijer, 2006, p. 1) and depends on individual's experience and knowledge (Dörner, 2001, pp. 58-62). The origin of the term complexity comes from the Latin words "complexus" and "complecti", which means "extensive, interrelated, confusing, entwined or twisted together" (ElMaraghy *et al.*, 2012, p. 794; Gießmann, 2010, p. 30; Grübner, 2007, pp. 40-41; Pfeifer *et al.*, 1989, p. 889). The term "complexity" is therefore often used synonymously with the term "complicated" (ElMaraghy *et al.*, 2012, pp. 794-795; Gießmann, 2010, p. 30), but the terms have specific characteristics and different meanings.

Within a company, product development is one of the most complex tasks and uncertain processes (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386) and has the biggest influence on a company's complexity (Krause, Franke and Gausemeier, 2007, pp. 3-15). For a new global economy's success, product development is the core process according to Ragatz, Handfield and Petersen (2002, p. 390). Product development's objective is "to translate an idea into a tangible physical asset" (Davila, 2000, p. 385). The time for product development of industrial goods has strongly decreased during the last years due to increasing globalization, customer's behavioral change and hardly predictable market fluctuations (Krause, Franke and Gausemeier, 2007, p. 89). Product development process is often the longest part of bringing a product to market (Govil and Proth, 2002, p. 103) and is confronted with several factors, such as demand variety, uncertain objectives, dynamics, high time pressure and restricted resources (Wildemann, 2012, p. 202). Generally, complexity in product development comes from a variety of internal and external sources (Dehnen, 2004, pp. 32-35), called complexity drivers. Complexity drivers play a significant role in complexity management. They describe the complexity in a system and help to evaluate and handle it (Vogel and Lasch, 2016, p. 2). For managing a system's complexity, an optimum fit between internal and external complexity is needed (Schuh, 2005, p. 43; Vogel and Lasch, 2015, p. 116). The management of complexity is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). For an effective and target-oriented complexity management, information is needed (Davila, 2000, pp. 386-387).

Based on scientific research, information can be gathered by conducting literature research or empirical studies. To verify existing knowledge or theories and to identify commonalities and differences, the results from literature and the real world are compared. In literature, several empirical studies regarding complexity management in various fields of industry and regions/countries already exist. They are focused on different fields in the company and along the value chain and were conducted in the time period between 1999 and 2015 (see subsection 4.2.3). There are also empirical studies regarding complexity management in the field product development and have been done by Li *et al.* (2005, pp. 2577-2579, 2583-2584), Kim and Wilemon (2009, pp. 547-550), Newman (2009, p. 2), Chronéer and Bergquist (2012, pp. 21-26), Kim and Wilemon (2012, pp. 1, 4-6) and Grussenmeyer and Blecker (2013, p. 140). The data collection was conducted in China, the United States of America, Sweden, Italy and Germany and in 14 different fields of industry (e.g. engineering, electrical, medical, chemical & pharmaceutical, clothing, etc.). Based on these studies, the impact of environmental complexity and the choice of management control systems and their effects on product development and their processes are investigated. Furthermore, the sources, which cause complexity and the consequences when complexity arises in new product development and especially in development projects, are identified and analyzed to increase transparency and understanding for an effective complexity management. In addition, the complexity level in new product development is analyzed and the question of how complexity can be reduced through standardization and modularization is discussed.

For an effective complexity management, it is necessary to identify the complexity sources, called complexity drivers and their effects first (Vogel and Lasch, 2016, p. 33). None of the previous empirical studies regarding complexity management in product development is concerned with the identification and analysis of complexity drivers and their effects. Furthermore, no comparison between the empirical findings and literature has been done in the previous empirical studies.

The purpose of this chapter is to close this research gap by providing an empirical research regarding complexity drivers and their effects to verify scientific findings and to compare the literature and the empirical results to identify similarities and differences. The perception between science and practice and their discrepancy is described and processed. A further contribution of this empirical study is to develop additional knowledge (scientific based – practice driven) according to complexity in product development for science and practice within a systematical and target-oriented data collection and the succeeding comparison of literature with the empirical results.

From scientific perspective, this empirical research establishes a connection between scientific research and the real world by answering the research questions (see section 4.2) within the systematically collected empirical data. It closes a currently existing gap in scientific literature by comparing the literature and empirical results to identify similarities and differences and to verify scientific findings. In addition to the comparison between the theoretical and the empirical results, the theoretical findings can also be confirmed, advanced or progressed within this empirical research. This study presents a theoretical overview about complexity drivers in product development and the existing empirical researches and gives the researcher an overview about what is already known in practice about these issues and practice's tendencies (empirical findings). Furthermore, the researcher gains some detailed information about the research and data collection methodology, the objectives and the sample description to increase transparency. This enables the researcher to reproduce the findings. Based on this study, researchers can build new ideas, theories and hypotheses for their own research. Within this research, the gaps for future research are pointed out.

From practical perspective, this empirical study gives the practitioner an overview about complexity perception in product development by other practitioners. Furthermore, the practitioner receives a differentiated overview of complexity in product development, which is perceived in different fields of industry. This study also answers the following manager's questions "What complexity sources (drivers) have a high influence on product development's complexity and thus are relevant for the company?" and "What effects does high complexity within the company have on product development?", by providing an overview about the main and relevant complexity drivers, which were assigned by the respondents with a strong or very strong influence on product development's complexity. Beyond, the practitioner gets an overview about the main topics and properties in product development with high complexity, which have a strong or very strong influence on product development's performance as said so by the respondents. This overview can increase transparency for the practitioner.

As already mentioned, different complexity drivers, focused on product development, are described in literature by several authors. To compare literature's findings with the practice, this empirical research was conducted. This research is structured as follows: In section 4.2, a literature overview about the complexity drivers in product development and their effects on company's complexity is given. Furthermore, an overview of existing empirical researches in the field of complexity management is described. The research methodology and objectives, questionnaire's design, as well as the data collection methodology and sample description are presented in section 4.3. The empirical findings are described in section 4.4. Furthermore, the results are compared with literature to identify commonalities and differences. Section 4.5 concludes the chapter with implications for future research and presents research's limitations.

4.2 Literature review

4.2.1 Research methodology and boundary definition

This research's purpose is to compare literature's findings regarding specific complexity drivers and their effects on company's complexity, especially in product development, with the real world to increase transparency and knowledge for science and practice by identifying similarities and differences. Furthermore, an overview about existing empirical studies in the field complexity management is presented. The empirical study was conducted in the manufacturing industry of Germany.

Before starting an empirical research, the existing literature regarding the complexity drivers and their effects, as well as the previous empirical studies must be reviewed. The following subsection presents a literature review about these 3 issues. For this literature review, we used the methodology of Fink (2014, pp. 3-5) and defined 2 research questions:

- RQ 1: What complexity drivers currently occur in the field product development in manufacturing companies in scientific literature? What effects do complexity drivers generally have on company's complexity?
- RQ 2: What empirical studies in the field complexity management currently exist in scientific literature? What objectives do they have and what research methodologies are applied? What empirical studies concern with specific complexity drivers and their effects?

Next, we defined the search terms and databases by following the methodology of Vogel and Lasch (2016, pp. 4-5) and Vogel (2017, pp. 94-95). The search terms are formulated based on the research questions. For search terms' formulation, we used a particular grammar and logic and combined the key words with specific Boolean operators (AND, OR and NEAR) analogously. The finalized search terms are created through an iterative process in order to identify all important literature sources. To extend the amount of relevant literature, the literature search was performed in English- and German-language literature and 8 different databases, which are specialized in science and economics: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink. Most of the databases are connected with other databases. For example, EBSCOhost and Google Scholar are connected with the databases Emerald, IEEE Xplore, ScienceDirect and SpringerLink. Since we want to compare our empirical findings with the existing literature in the same time period, the time period of our literature research was restricted between 1900/01/01 and 2015/12/31, because our empirical study was performed in the years 2015 and 2016. The literature search resulted in a certain amount of literature sources (complexity drivers and their effects: 911 literature sources; previous empirical studies in the field complexity management: 26,699 literature sources) and comprises research papers from journals, conference proceedings, books, essays and PhD theses. Several literature sources were found more than once.

Answering the first and second research question, the existing literature was analyzed, evaluated and synthesized based on the research questions by using qualitative data analysis techniques to identify the relevant literature sources. Literature research always accumulates many publications, but only a few are relevant for scientific research (Fink, 2014, p. 5). Synthesizing the results of the literature research is therefore necessary to identify the relevant literature sources. For the qualitative data analysis, we used the methodology of Vogel and Lasch (2016, pp. 6-7), which is described in detail in their publication. In the following subsections 4.2.2 and 4.2.3, the results of our literature research are described.

4.2.2 Complexity drivers in product development and their effects on company's complexity

The result of our literature research is a systematic, explicit and reproducible literature review about complexity drivers in manufacturing companies and along the value chain, published by Vogel and Lasch. In their literature review, Vogel and Lasch identified different definitions about complexity drivers and generated a more general definition of complexity drivers (Vogel and Lasch, 2016, pp. 17-18). Further, they described a variety of methods for complexity driver's identification, operationalization and visualization and presented several different complexity drivers, which occur in manufacturing companies and along the value chain, including the field product development. Based on literature, complexity drivers have a direct influence on the company and the total value chain (Schuh, 2005, pp. 8-19). The knowledge about complexity drivers is necessary to develop an effective complexity strategy (Serdarasan, 2011, p. 792). As already mentioned, product development has the biggest influence on a company's complexity (Krause, Franke and Gausemeier, 2007, pp. 3-15). The first step in developing and implementing a target-oriented complexity management in a company and finally in product development is to identify the corresponding complexity drivers (Fleck, 1995, pp. 178-180; Giannopoulos, 2006, pp. 154-156; Perona and Miragliotta, 2004, p. 106). Keuper (2004, p. 82) followed this argumentation and described that the handling of company's complexity depends on the complexity drivers. In their literature review, Vogel and Lasch (2016, p. 18) defined complexity drivers as "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. Complexity drivers are influenced by one another, that is by internal or external drivers, and cannot be reduced completely to another one".

According to their origin, complexity drivers can be separated in internal and external drivers (Blecker, Kersten and Meyer, 2005, pp. 48-51; Kersten *et al.*, 2006, pp. 326, 337; Zahn, Kapmeier and Tilebein, 2006, pp. 142-143). Furthermore, internal complexity drivers can be differentiated in correlated and autonomous complexity drivers (Bliss, 2000, pp. 4-7, 65-66, 163-169). Correlated complexity drivers have a direct correlation to external complexity and are influenced by it. Autonomous complexity drivers are not influenced by external factors and the company itself determines them. Internal and external complexity drivers are connected directly and induce system's complexity (Belz and Schmitz, 2011, pp. 185-186; Collinson and Jay, 2012, pp. 7-8; Götzfried, 2013, pp. 35-38, 67-68; Grimm, Schuller and Wilhelmer, 2014, pp. 91-93; Größler, Grübner and Milling, 2006, p. 256). They cannot be separated selectively and they cannot be operationalized (Bohne, 1998, pp. 58-59; Götzfried, 2013, pp. 67-68; Schmidt, 1992, p. 14; Schuh and Schwenk, 2001, pp. 10-13).

In the literature review from Vogel and Lasch (2016, pp. 41-53), 17 publications regarding complexity drivers in product development were found between 1998 and 2015. No publications were found before 1998. Between 2010 and 2015, 65% of the publications were published. This trend shows an increased interest throughout the last years and it can be derived that complexity drivers in product development become more and more important in scientific research.

Furthermore, 108 different complexity drivers in product development were found in the literature review from Vogel and Lasch (2016). The identified complexity drivers were clustered in different main complexity driver categories depending on their origin, characteristics and influence on other drivers. The classification system consists of 3 main groups (external complexity, internal complexity and general complexity), 4 subcategories (society complexity, market complexity, internal correlated complexity and internal autonomous complexity) and 22 main complexity driver categories (society, demand, competitive, supply, technological external, target, customer, product & product portfolio, technological internal, product development, supply process, service, remanufacturing, organizational, process, production, planning, control & information, resource, logistics, sales & distribution, general complexity). As a result of complexity drivers' clustering, 27 external (25%), 32 internal correlated (30%) and 49 internal autonomous complexity drivers (45%) were found and identified in literature. Most of the identified complexity drivers were assigned to the main group internal complexity. Thus, this group is mostly influenced by complexity and must be handled first (Vogel and Lasch, 2016, pp. 27-35).

Table 14 presents the identified complexity drivers in the field product development (PD) and their literature occurrence. The most referred complexity drivers are organizational complexity (N: 6), process complexity (N: 5) and product structure/design (N: 5). As also seen in Table 14, some authors appointed more complexity drivers than other authors in the field product development. The amount of complexity drivers in a system, especially in product development, reflects the level of difficulty in managing a system's complexity, because complexity drivers have a high influence on a system's complexity. The number of identified complexity drivers in product development ranges from 2 up to 38 (see Table 14) and depends on the situation and the eye of the beholder. In the complexity driver categories supply complexity, supply process complexity, service complexity and remanufacturing complexity, no specific complexity drivers were appointed by the authors. It seems that these categories are not as relevant for product development from literature's point of view. Based on these results, in practice, the same or other complexity drivers can occur from our point of view. For example, the category remanufacturing complexity could be relevant for product development's complexity, because in product development, product's structure, materials and functions are defined and these are relevant for product's remanufacturing. Thus, an empirical research must be performed to identify new complexity drivers or to confirm the existing drivers. In the end, the empirical results are compared with the results from literature to identify commonalities and differences. For designing the questionnaire of our empirical research, only the literature sources, which were published before 2015 were considered, because the empirical research started already in 2014 with the pretest. After the pretest, the final questionnaire started at the beginning of the year 2015. The publications from Bosch-Rekveldt *et al.* (2015, p. 1099) and Oyama, Learmonth and Chao (2015, p. 5) were not yet published at the time the questionnaire started and thus their findings were not implemented in questionnaire's design.

Table 14: Overview of the main complexity drivers in the field PD and their literature occurrence (Part A)

Explanation:

* Complexity drivers, which are out of focus according to questionnaire's design, because they were published after the year 2014 (Focus for questionnaire's design: complexity drivers, which were published between 1998 and 2014)

Origin		**Complexity driver category and its drivers**	Komorek (1998, p. 213)	Wangenheim (1998b, pp. 30-33)	Kim and Wilemon (2003, pp. 18-22)	Dehnen (2004, pp. 32-35)	Giannopoulos (2006, p. 155)	Krause, Franke and Gausemeier (2007, pp. 5-10)	Grussenmeyer and Blecker (2010, pp. 53-54)	Eigner, Anderl and Stark (2012, pp. 7-10)	ElMaraghy *et al.* (2012, p. 798)	Schömann (2012, pp. 135-138)	Zhang and Yang (2012, pp. 231-232)	Budde and Golovatchev (2014, p. 602)	Jensen, Bekdik and Thuesen (2014, p. 541)	Lucae, Rebentisch and Oehmen (2014, pp. 658-659)	Thiebes and Plankert (2014, pp. 171-172)	Bosch-Rekveldt *et al.* (2015, p. 1099)	Oyama, Learmonth and Chao (2015, p. 5)	**Literature occurrence (Total)**
External complexity	**Society complexity**	• Social framework *																•		**1**
		• Value change & value awareness						•												**1**
		• Environmental complexity (general)				•							•			•				**3**
		• Dynamic & change of company's environment *																•		**1**
		• Ecological conditions/factors						•												**1**
		• Legal factors						•												**1**
		• Political framework conditions											•					•		**2**
		• Country-specific requirements *																•		**1**
		• Change of populations structure						•												**1**
		• Standards and regulations						•												**1**
		• Turbulences in company's environment											•							**1**
		• Uncertainty in company's environment *																•		**1**
		• Interdependencies between environmental factors											•					•		**2**
	Market complexity	**General market-related complexity**																		
		Market complexity (general)			•				•		•									3
		Market's change						•												1
		Market's globalization						•												1
		Market's dynamics											•							1
		Market's protectionism						•												1
		Demand complexity																		
		Demand complexity (general)				•						•								2
		Individuality of customer demands						•												1

Table 14: Overview of the main complexity drivers in the field PD and their literature occurrence (Part B)

Explanation:

* Complexity drivers, which are out of focus according to questionnaire's design, because they were published after the year 2014 (Focus for questionnaire's design: complexity drivers, which were published between 1998 and 2014)

Origin		Complexity driver category and its drivers	Komorek (1998, p. 213)	Wangenheim (1998b, pp. 30-33)	Kim and Wilemon (2003, pp. 18-22)	Dehnen (2004, pp. 32-35)	Giannopoulos (2006, p. 155)	Krause, Franke and Gausemeier (2007, pp. 5-10)	Grussenmeyer and Blecker (2010, pp. 53-54)	Eigner, Anderl and Stark (2012, pp. 7-10)	ElMaraghy *et al.* (2012, p. 798)	Schömann (2012, pp. 135-138)	Zhang and Yang (2012, pp. 231-232)	Budde and Golovatchev (2014, p. 602)	Jensen, Bekdik and Thuesen (2014, p. 541)	Lucae, Rebentisch and Oehmen (2014, pp. 658-659)	Thiebes and Plankert (2014, pp. 171-172)	Bosch-Rekveldt *et al.* (2015, p. 1099)	Oyama, Learmonth and Chao (2015, p. 5)	**Literature occurrence (Total)**
External complexity	Market complexity	**Competitive complexity**																		
		Competitive complexity (general)				•						•								2
		Number and strength of competitors											•					•		2
		Competitive pressure						•												1
		Supply complexity																		
		Technological complexity (external)																		
		External technological complexity (general)				•														1
		Technological progress						•					•							2
		Technological innovations and availability						•												1
		New technologies and materials						•												1
Internal complexity (Part I)	Internal correlated complexity	**Target complexity**																		
		Target complexity (general)				•						•								2
		Amount of different targets *																•		1
		Conflict between different targets *																•		1
		Ambiguity of targets *																•		1
		Customer complexity																		
		Customer structure										•								1
		Product & product portfolio complexity																		
		Product complexity (general)									•	•	•				•			4
		Product portfolio complexity (general)										•				•				2
		Product variety		•				•		•							•			4
		Product range/portfolio		•				•		•							•			4
		Product structure/design		•		•				•			•		•					5
		Product technology	•																	1
		Component type					•													1
		Variety of parts and modules	•	•			•												•	4
		Property of parts and modules	•	•			•												•	4
		Variety of the applied materials	•																	1
		Property of the applied materials	•																	1
		Quality standards *																•		1
		Conflicts between different standards *																•		1

Table 14: Overview of the main complexity drivers in the field PD and their literature occurrence (Part C)

Explanation:
* Complexity drivers, which are out of focus according to questionnaire's design, because they were published after the year 2014 (Focus for questionnaire's design: complexity drivers, which were published between 1998 and 2014)

Origin		Complexity driver category and its drivers	Komorek (1998, p. 213)	Wangenheim (1998b, pp. 30-33)	Kim and Wilemon (2003, pp. 18-22)	Dehnen (2004, pp. 32-35)	Giannopoulos (2006, p. 155)	Krause, Franke and Gausemeier (2007, pp. 5-10)	Grussenmeyer and Blecker (2010, pp. 53-54)	Eigner, Anderl and Stark (2012, pp. 7-10)	ElMaraghy *et al.* (2012, p. 798)	Schömann (2012, pp. 135-138)	Zhang and Yang (2012, pp. 231-232)	Budde and Golovatchev (2014, p. 602)	Jensen, Bekdik and Thuesen (2014, p. 541)	Lucae, Rebentisch and Oehmen (2014, pp. 658-659)	Thiebes and Plankert (2014, pp. 171-172)	Bosch-Rekveldt *et al.* (2015, p. 1099)	Oyama, Learmonth and Chao (2015, p. 5)	**Literature occurrence (Total)**
Internal complexity (Part I)	**Internal correlated complexity**	**Technological complexity (internal)**																		
		Technology complexity (general)			•				•				•			•				4
		Technology change/innovation															•			1
		New technologies *																•		1
		Number of different applied technologies		•																1
		Technological uncertainty *																•		1
		Hardware and software complexity (general)					•													1
		Type of data medium					•													1
		Size of data medium					•													1
		Type of interfaces					•													1
		Amount of interfaces					•													1
		Criteria of hardware and software tests					•													1
		Product development complexity																		
		Development complexity (general)			•				•											2
		Development program's complexity				•														1
		Applied methods or instruments						•												1
		Supply process complexity																		
		Service complexity																		
		Remanufacturing complexity																		

Table 14: Overview of the main complexity drivers in the field PD and their literature occurrence (Part D)

Explanation:
* Complexity drivers, which are out of focus according to questionnaire's design, because they were published after the year 2014 (Focus for questionnaire's design: complexity drivers, which were published between 1998 and 2014)

Origin		Complexity driver category and its drivers	Komorek (1998, p. 213)	Wangenheim (1998b, pp. 30-33)	Kim and Wilemon (2003, pp. 18-22)	Dehnen (2004, pp. 32-35)	Giannopoulos (2006, p. 155)	Krause, Franke and Gausemeier (2007, pp. 5-10)	Grussenmeyer and Blecker (2010, pp. 53-54)	Eigner, Anderl and Stark (2012, pp. 7-10)	ElMaraghy *et al.* (2012, p. 798)	Schömann (2012, pp. 135-138)	Zhang and Yang (2012, pp. 231-232)	Budde and Golovatchev (2014, p. 602)	Jensen, Bekdik and Thuesen (2014, p. 541)	Lucae, Rebentisch and Oehmen (2014, pp. 658-659)	Thiebes and Plankert (2014, pp. 171-172)	Bosch-Rekveldt *et al.* (2015, p. 1099)	Oyama, Learmonth and Chao (2015, p. 5)	**Literature occurrence (Total)**
Internal complexity (Part II)	Internal autonomous complexity	**Organizational complexity**																		
		Organizational complexity (general)			•				•		•	•	•			•				6
		Organization's structure			•			•												2
		Deficits in organization structure *																•		1
		Organization's/Company's size															•			1
		Company's location *																•		1
		Company's management *																•		1
		Business segment/industrial sector															•			1
		Company's strategy (strategical complexity)						•					•			•				3
		Complexity between cooperation partners						•	•											2
		Force within the company *																•		1
		Handling of risks, uncertainty and incidence *																•		1
		Employee complexity (general)						•								•				2
		Employee's experience *																•		1
		Employee's qualification *																•		1
		Employee's behavior *																	•	1
		Number of tasks *																•		1
		Task's variety *																•		1
		Dependencies between different tasks *																•		1
		Number of different languages in the company *																•		1
		Number of different nationalities in the company *																•		1
		Number of different time zones *																•		1
		Number of joint-ventures *																•		1
		Number of contractual partners *																•		1
		Number of different financial sources *																•		1
		Confidence in contractual partners *																•		1
		Lack of transparency (general)						•												1
		Lack of cost transparency						•												1
		Lack in consistency of activities						•												1
		Process complexity																		
		Process complexity (general)				•					•	•	•			•				5
		Variety of processes							•											1
		Number of process interfaces *																•		1

Table 14: Overview of the main complexity drivers in the field PD and their literature occurrence (Part E)

Explanation:

* Complexity drivers, which are out of focus according to questionnaire's design, because they were published after the year 2014 (Focus for questionnaire's design: complexity drivers, which were published between 1998 and 2014)

Origin		Complexity driver category and its drivers	Komorek (1998, p. 213)	Wangenheim (1998b, pp. 30-33)	Kim and Wilemon (2003, pp. 18-22)	Dehnen (2004, pp. 32-35)	Giannopoulos (2006, p. 155)	Krause, Franke and Gausemeier (2007, pp. 5-10)	Grussenmeyer and Blecker (2010, pp. 53-54)	Eigner, Anderl and Stark (2012, pp. 7-10)	ElMaraghy *et al.* (2012, p. 798)	Schömann (2012, pp. 135-138)	Zhang and Yang (2012, pp. 231-232)	Budde and Golovatchev (2014, p. 602)	Jensen, Bekdik and Thuesen (2014, p. 541)	Lucae, Rebentisch and Oehmen (2014, pp. 658-659)	Thiebes and Plankert (2014, pp. 171-172)	Bosch-Rekveldt *et al.* (2015, p. 1099)	Oyama, Learmonth and Chao (2015, p. 5)	**Literature occurrence (Total)**
Internal complexity (Part II)	Internal autonomous complexity	**Production complexity**																		
		Production complexity (general)	●									●								2
		Production structure													●					1
		Number of production locations *																●		1
		Manufacturing technology	●																	1
		Uncertainties in production methods *																●		1
		Maintenance complexity (general)	●																	1
		Planning, control and information complexity																		
		Planning, control and information complexity (general)										●								1
		Project time *																●		1
		Time pressure in project planning *																●		1
		Project team *																●		1
		Lack in strategic planning						●												1
		Organization's information technology systems						●												1
		Resource complexity																		
		Resources' shortage *																●		1
		Logistics complexity																		
		Supply chain complexity (general)								●										1
		Sales and distribution complexity																		
		Distribution complexity (general)	●																	1
		Marketing complexity (general)			●				●											2
General complexity		Variety/Multiplicity												●						1
		Dynamics												●						1
Total amount of complexity drivers cited in literature source:			**7**	**5**	**6**	**8**	**8**	**25**	**7**	**4**	**4**	**10**	**13**	**2**	**2**	**7**	**6**	**38**	**2**	

For a complexity management, it is necessary to identify and analyze the effects of high complexity and its origin within the company (Kersten, Koppenhagen and Meyer, 2004, pp. 211-214). In literature, the authors describe several effects of high complexity. Furthermore, effects of high complexity are divided in different categories, although the differentiation in 2 categories is preferred in literature.

For example, Meyer (2007, p. 31) divides the effects of high complexity in 2 categories: General effects and effects on company's cost level. Keuper (2004, pp. 93-94) specifies the effects into cost effects and divides them also in 2 categories: Direct costs (e.g. costs for product development or prototype testing) and time-delayed costs (e.g. cost for employees or data processing). Schuh and Schwenk (2001, p. 19), Schuh (2005, p. 21) and Thiebes and Plankert (2014, p. 173) divide the effects of high complexity also in 2 categories: Direct effects (e.g. costs for product and product development process or quality management) and indirect effects (e.g. product cannibalization or distribution system's effectiveness). However, the divisions, made by the already mentioned authors, are fairly equal to Keuper's classification. In contrast, Gießmann (2010, pp. 39-41) divides the effects of high complexity into 4 main categories: Time (e.g. time for quality checks or process time), quality (e.g. process balance or adherence to deadlines), costs (e.g. direct costs or indirect costs) and flexibility (e.g. design flexibility or process flexibility). Furthermore, Meyer (2007, pp. 186-187) divides the effects of high complexity into 11 main categories: Procurement (e.g. inventory or resource planning), research and development (e.g. development process of new products or product tests), costs (e.g. development costs or coordination costs), logistics (e.g. inventory or amount of required resources), marketing (e.g. pricing or product reclamation), product (e.g. product design), production (e.g. amount of required tools or controlling effort), process (e.g. process planning and controlling or coordination effort), total company (e.g. quality or efficiency), management and controlling (e.g. calculation effort or economy) and other parts (e.g. delivery time or supplied goods or resource variety). Wildemann (2012, p. 114), Benett (1999, p. 32), Schuh and Schwenk (2001, pp. 20-22) and Schuh (2005, pp. 22-24) assign the complexity effects based on variety to the specific parts of the value chain and describe 7 categories: Supplier (e.g. outsourcing complexity), research and development (e.g. effort for product development or product tests), procurement and logistics (e.g. stocks or material staging), production (e.g. quality or preproduction costs), distribution (e.g. marketing costs or coordination effort), distribution channel (e.g. costs for product handling or forecast's accuracy) and after-sales service (e.g. stockpiling of spare parts or training for staff members).

For effect's classification, we analyzed the specific effects from different authors and created intersections between the mentioned complexity effects. In general, we found out that most of the mentioned complexity effects can be aggregated in 4 main categories. Keuper (2004, pp. 90-97), Schuh and Schwenk (2001, pp. 17-22), Thiebes and Plankert (2014, p. 173), Gießmann (2010, pp. 39-41), Meyer (2007, pp. 31, 186-187), Wildemann (2012, p. 114), Benett (1999, p. 32) and Schuh (2005, pp. 19-24) assigned complexity effects under the categories time, quality and costs. Gießmann (2010, p. 40) extended the main categories by adding the category flexibility. In our general framework, we defined 4 main categories for the complexity effects based on literature: Time, quality, costs and flexibility.

Based on the already mentioned categories from different parts of the value chain, which were found in literature, we defined a more general framework for identification, analyzing and evaluation of the complexity effects along the value chain. In general, the value chain is separated in 7 different fields according to

Vogel and Lasch (2016, pp. 14-15): Product development, procurement/purchasing, logistics, production, order processing/distribution/sale, internal supply chain and remanufacturing (see Figure 10).

This framework is the basis for identification, analysis and evaluation of the complexity effects in product development within our empirical study, because the field product development is also a part of the value chain.

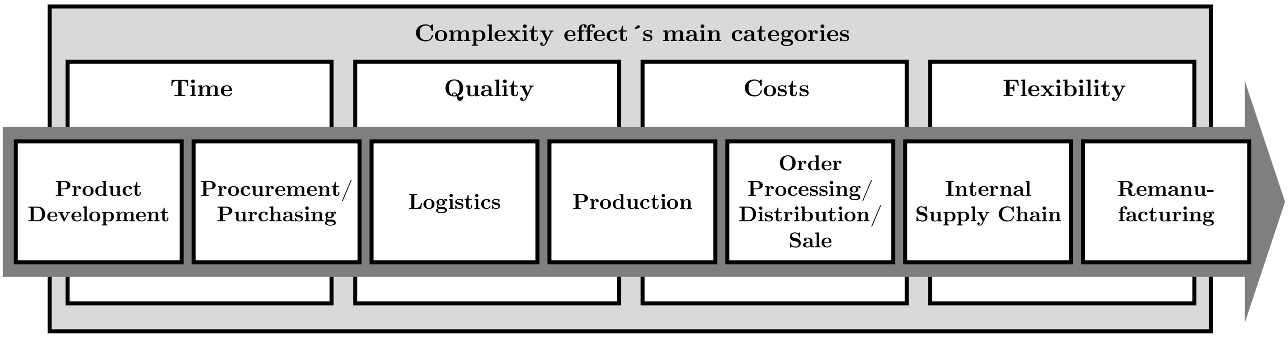


Figure 10: General framework for identification, analysis and evaluation of the complexity effects in the company and along the value chain

4.2.3 Overview of existing empirical studies

For a researcher, it is important to review existing empirical studies in the same or a similar scientific area before starting an empirical research, because it allows him to get an overview about their objectives, research methodologies and findings (Madu, 1998, pp. 354-355). Theories and statements in literature and practice can change over time, so it is important to determine and to review the practical side through an empirical research (Jasti and Kodali, 2014, pp. 1080-1081, 1090-1091, 1096).

Following Madu (1998), another literature research was performed analogously to the literature research about complexity drivers and their effects (see subsection 4.2.1 and see Table 48 in the appendix). The objective was to identify all existing empirical researches concerning complexity management in manufacturing companies and focusing on complexity drivers and their effects on company's complexity during the last years. The literature research resulted in 72 different empirical studies in the time period between 1999 and 2015, which are focused on complexity management. These studies were analyzed and synthesized regarding their content, research objectives, focus, field of industry, region/country, research period and applied data collection methodology. The conducted empirical researches analyzed company's complexity with different objectives, data collection methodologies and focuses. Table 15 presents the results of our literature analysis.

The empirical studies are focused on 8 different fields: General in manufacturing companies (N: 32; 44%), product development (N: 6; 8%), production (N: 3; 4%), logistics (N: 5; 7%), order processing/distribution/ sale (N: 4; 6%), internal supply chain (N: 16; 22%), remanufacturing (N: 2; 3%) and other fields (N: 4; 6%) (see Table 15). Most of the empirical studies are focused on the fields general in manufacturing companies and internal supply chain. The most applied data collection methodologies are questionnaires (N: 37) and expert interviews (N: 41).

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part A)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/ country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

						Applied data collection method, sample size and amount of received data						
Author(s)	**Research objectives**	**Focus**	**Field(s) of industry**	**Region/ Country**	**Research's period** (mm/yyyy)	**Questionnaire**	**Expert interviews**	**Workshop(s)**	**Case study**	**Observation**	**Documentary analysis**	**Not specified**
Ashmos, Duchon and McDaniel (2000, pp. 584-588)	Identification of organizational responses to environmental complexity.	G	Medical Industry	State of Texas, USA	1990	710 (back 164)			8	2		
Beutin (2000, pp. 98-104)	Identification of product complexity's influence on customer's benefit.	G	Engineering / Electrical / Metal / Petroleum & Plastics / Chemical / Leather, Glas, Ceramic, Pit & Quarry / Transport	USA, Germany	03/1998 - 07/1998	4,800 (back 981)						
Maune (2001, pp. 58-84)	Analysis of complexity in the automotive industry.	G	Automotive / Engineering	Germany	- - -	1,300 (back 126)						
Novak and Eppinger (2001, pp. 194-195)	Analysis of the connection between product complexity and vertical integration.	G	Automotive	USA, Europe, Japan	- - -		More than 1,000					
Chapman and Hyland (2004, pp. 553, 555-557)	Identification and analysis of the aspects of complexity regarding product, process, technological and customer interface.	G	- - -	Sweden, Ireland, Italy, Netherlands, UK and Australia	- - -	70 (back - - -)		70	70			
Purle (2004, pp. 143-279)	Identification of the influences on complexity and resources induced by company growth.	G	Information Technology / Biotechnology / Material Industry	Germany	12/2001 - 12/2002		20		3			
Eichen *et al.* (2005, p. 123)	Analysis of complexity in the company.	G	- - -	- - -	- - -		More than 50					
PricewaterhouseCoopers (2006) (cited in Schömann, 2012, p. 142)	Identification of management's complexity perception in the company.	G	- - -	Worldwide	- - -							X X
Scheiter, Scheel and Klink (2007)	Analysis of the question how much complexity really costs.	G	- - -	- - -	- - -							X X
Schuh *et al.* (2007b, pp. 6-7)	Analysis of complexity in the automotive industry.	G	Automotive	- - -	- - -		X					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part B)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/ country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data						
						Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Closs *et al.* (2008, pp. 590-594, 600)	Identification and analysis of the significant dimensions of product portfolio complexity.	G	Automotive / Engineering / Optics / Computer Industry / Telecommunication / Aircraft	USA	2005 - 2006		63		6	6		
Maylor, Vidgen and Carver (2008, pp. 15, 17-18)	Identification and analysis of project manager's perceptions regarding managerial complexity and what makes a project complex to manage.	G	- - -	- - -	- - -	128 (back - - -)		1				
Bayer (2010, pp. 149-155)	Identification of complexity factors and their influences in different company divisions during new product development.	G	- - -	Germany	- - -	125 (back 107)						
Gießmann and Lasch (2010, pp. 152-155)	Analysis of company's complexity and demonstration of the relevance for organizations.	G	Engineering	Germany	- - -	1,496 (back 236)						
Palmisano (2010, pp. 1-10)	Analysis of capitalizing based on complexity, its increase and effective handling.	G	33 Industries in the sectors: public, communications, industrial, distribution, financial services	Worldwide (in 60 countries)	09/2009 – 01/2010		1,541					
Schoenherr *et al.* (2010, pp. 639-644)	Identification and analysis of enterprise system's complexity.	G	Engineering	Germany	- - -		More than 36		18			
Bosch-Rekveldt *et al.* (2011, pp. 728-729, 732-733)	Identification of the elements, which contribute to project's complexity.	G	Process Engineering	Europe, Asia, Middle-America	- - -		18					
Parry, Purchase and Mills (2011, pp. 67-68, 72-73)	Analysis of the nature of complexity and the factors that arise in high value contracts between large organizations.	G	Engineering Service Industry	- - -	2008		28					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part C)

Explanation according to focus and occurrence in literature:

- G General in manufacturing companies (N: 32)
- PD Product development (N: 6)
- PR Production (N: 3)
- L Logistics (N: 5)
- OPD Order Processing/Distribution/Sale (N: 4)
- SC Internal Supply Chain (N: 16)
- R Remanufacturing (N: 2)
- OF Other fields (N: 4)

Explanation according to field(s) of industry, region/ country, research's period and sample size:

- \- - - No information referred
- X Applied, but no sample size is referred
- X X No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data: Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Wildemann and Voigt (2011, pp. 113-170)	Identification of complexity drivers, their influences and approaches for complexity management in manufacturing companies.	G	Automotive / Engineering / Metal / Plastics / Medical Industry	Germany	2010-2011	2,132 (back 248)	26	4	27			
Brexendorf (2012, pp. 71-76, 330-338)	Identification and analysis of complexity in co-operations.	G	Automotive / Engineering / Electrical / Chemical & Pharmaceutical / Others	Germany, Switzerland, Luxembourg, Netherlands, Hungary	06/2006 - 09/2006	405 (back 60)						
Collinson and Jay (2012, pp. 13-14, 251-286)	Identification of complexity drivers and their influences on company's performance.	G	Pharmaceutical / Banking / Insurance	Worldwide	2005 - 2010		200	200	200		200	
Schey and Roesgen (2012, pp. 30-33)	Identification and analysis of management's perception regarding complexity in their company.	G	Chemical & Pharmaceutical / Consumer Goods	Europe	- - -							X X
Schömann (2012, pp. 127-159)	Identification and analysis of complexity perception in the automotive industry.	G	Automotive	- - -	- - -							X X
VDI (2012) (cited in Brandes and Brandes, 2014, p. 12)	Analysis of the complexity perception in the company.	G	- - -	Germany	05/2012	n.n.	X					
Götzfried (2013, pp. 20-24)	Analysis and evaluation of company's complexity induced by product variety.	G	Automotive / Engineering / Consumer Goods	- - -	- - -	175 (back - - -)	49	21	17			
Hanisch and Wald (2013, pp. 101-103)	Identification of complexity drivers in project management.	G	Automotive / Engineering / Electrical / Chemical & Pharmaceutical / Information Technology / Telecommunication / Puplic Administration / Finance / Provider	Germany, Austria, Switzerland	- - -	X (back 218)						

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part D)

Explanation according to focus and occurrence in literature:
G General in manufacturing companies (N: 32)
PD Product development (N: 6)
PR Production (N: 3)
L Logistics (N: 5)
OPD Order Processing/Distribution/Sale (N: 4)
SC Internal Supply Chain (N: 16)
R Remanufacturing (N: 2)
OF Other fields (N: 4)

Explanation according to field(s) of industry, region/ country, research's period and sample size:
- - - No information referred
X Applied, but no sample size is referred
X X No data collection method and sample size referred

						Applied data collection method, sample size and amount of received data						
Author(s)	**Research objectives**	**Focus**	**Field(s) of industry**	**Region/ Country**	**Research's period** (mm/yyyy)	**Questionnaire**	**Expert interviews**	**Workshop(s)**	**Case study**	**Observation**	**Documentary analysis**	**Not specified**
Schuh, Froitzheim and Sommer (2013)	Analysis of management's perception regarding complexity in company's processes.	G	- - -	- - -	- - -							228
Jäger *et al.* (2014, pp. 645-646)	Identification and analysis regarding complexity in value networks.	G	- - -	- - -	- - -		190	190				
Schatz, Schöllhammer and Jäger (2014, pp. 687-689)	Analysis of management's perception regarding complexity in their company.	G	Automotive / Engineering / Electrical / Others	Germany	Spring 2013	200 (back - - -)						
Schöllhammer, Jäger and Bauernhansl (2014, pp. 3-4)	Identification and analysis of company's complexity level, the complexity perception in the company and the current applied strategies and approaches for complexity handling.	G	Automotive / Engineering / Electrical / Plastics / Chemical / Food / Printing / Aircraft / Information Technology / Service / Consumer Goods / Packaging Industry	Germany	07/2014 – 10/2014	192 (back - - -)						
Wölfling (2014, pp. 13-17)	Analysis of different kinds of complexity and the application of complexity management strategies and approaches.	G	Engineering / Electrical / Petroleum & Gas / Chemical / Automation / Energy / Traffic & Infrastructure / Telecommunication / Others	Germany	- - -	65 (back 41)						
Tresselt (2015, pp. 107-130)	Investigation of the question how current standards of project management address complexity and how complex products can be handled adequately.	G	- - -	Germany	09/2013 - 06/2014	4,900 (back 176)	36					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part E)

Explanation according to focus and occurrence in literature:
G General in manufacturing companies (N: 32)
PD Product development (N: 6)
PR Production (N: 3)
L Logistics (N: 5)
OPD Order Processing/Distribution/Sale (N: 4)
SC Internal Supply Chain (N: 16)
R Remanufacturing (N: 2)
OF Other fields (N: 4)

Explanation according to field(s) of industry, region/country, research's period and sample size:
- - - No information referred
X Applied, but no sample size is referred
X X No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data: Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Li *et al.* (2005, pp. 2577-2579, 2583-2584)	Analysis of the impact of environmental complexity on the choice of management control systems and their effects on product development and process decisions.	PD	Engineering / Electrical / Metal & Materials / Chemical & Pharmaceutical / Food / Clothing & Textile / Telecommunication / Commercial Products / Others	China	11/2002	850 (back 607)						
Kim and Wilemon (2009, pp. 547-550)	Identification and analysis of the conditions, which cause complexity in new product development to increase the understanding of an effective complexity management and methods for complexity handling.	PD	Engineering / Electrical / Industrial Photographic Paper / Medical Industry / Heating, Ventilating & Air Conditioning Industry	States of New York and Conneticut, USA	- - -		32					
Newman (2009, p. 2)	Analysis of the complexity of global new product development and discussion of the question how complexity can be reduced through standardization and component modularization.	PD	- - -	- - -	- - -		16				X	
Chronéer and Bergquist (2012, pp. 21, 24-26)	Identification and analysis of complexity regarding R&D-projects.	PD	Metal / Rubber & Plastics / Chemical / Papers / Mining / Food & Dairy	Sweden	- - -		71		50	50		
Kim and Wilemon (2012, pp. 1, 4-6)	Increasing the understanding of the consequences in new product development projects when complexity arises and the competitive advantages for companies that effectively manage complexity.	PD	Engineering / Electrical / Industrial Photographic Paper / Medical Industry / Heating, Ventilating & Air Conditioning Industry	States of New York and Conneticut, USA	- - -		32					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part F)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data: Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Grussenmeyer and Blecker (2013, p. 140)	Analysis of project's complexity level in the new product development and evaluation of a specific complexity management.	PD	- - -	Germany, Italy	01/2011 - 06/2011	23 (back - - -)						
Größler, Grübner and Milling (2006, pp. 254-255, 260-261)	Identification of complexity drivers in production.	PR	Engineering	Europe, South America, Asian Pacific Area	2002	558 (back - - -)						
Grübner (2007, pp. 167-174)	Identification of complexity drivers and their influences in production in the metal and electrical industry.	PR	Engineering / Electrical & Optics / Metal	Worldwide	2003	558 (back - - -)						
Fässberg *et al.* (2011, pp. 1-3)	Identification and analysis of production complexity from the perspective of different functions or roles within the production system.	PR	Automotive / Electrical	Sweden	09/2010 - 12/2010		X	X		3		
Westphal (2001, appendix, pp. I-III)	Analysis of complexity in manufacturing logistics.	L	Engineering / Metal	Germany	1995 - 1997	380 (back 66)						
Mayer (2007, pp. 63-106)	Identification of complexity drivers and applied management methods in logistics.	L	Automotive / Engineering / Furniture / Safety	Germany	- - -		5			5		
Meyer (2007, pp. 85-88, 190-206)	Analysis of logistic's complexity, identification of complexity drivers and their influences.	L	Automotive / Medical Industry / Logistics Service Industry	- - -	11/2005 - 04/2006	22 (back - - -)	8	25				
Gießmann (2010, pp. 87-92, 364-368)	Analysis of complexity and its perception in procurement logistics.	L	Automotive / Engineering / Electrical / Metal / Plastics / Chemical & Pharmaceutical / Glas, Ceramic, Pit & Quarry / Food / Lumber, Papers & Furniture / Clothing & Textile / Aircraft / Others	Germany	2008	1,496 (back 236)						

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part G)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/ country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data: Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
BVL (2014, p. 866)	Analysis of the current status regarding complexity management and its handling in the field of logistics.	L	Manufacturing Industry / Trading / Logistics Service Industry	Germany	Summer 2014	104 (back - - -)						
Raufeisen (1999, pp. 147-171)	Evaluation of complexity in the field order processing.	OPD	Engineering / Metal	- - -	- - -		X		3		X	
Buob (2010, pp. 48-93)	Analysis and evaluation of order processing complexity.	OPD	Insurance	Switzerland	- - -	2,680 (back 341)	17					
Kersten, Lammers and Skirde (2012, pp. 46-50)	Analysis of complexity perception in the field of distribution. Identification of complexity drivers and development of approaches for complexity improvement.	OPD	- - -	Germany	06/2010 - 10/2011		8	3	8			
Lammers (2012, pp. 65-84)	Analysis of complexity perception in the field of distribution. Identification of complexity drivers and development of approaches for complexity improvement.	OPD	Chemical / Medical Industry / Safety Equipment / Wholesale / Service Industry / Transport / Maritime Industry	Germany	06/2010 - 10/2011		8	3	8			
Miragliotta, Perona and Portioli-Staudacher (2002, pp. 392-395)	Analysis of supply chain complexity in the Italian household appliance industry.	SC	Household Appliance Industry	Italy	- - -		X		13			
Perona and Miragliotta (2004, pp. 103, 106-107)	Investigation of the question how complexity can affect manufacturing company's performances and its supply chain.	SC	Household Appliance Industry	Italy	- - -	X	X		14			

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part H)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	**Research objectives**	**Focus**	**Field(s) of industry**	**Region/ Country**	**Research's period** (mm/yyyy)	**Applied data collection method, sample size and amount of received data:** Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Geimer (2005, pp. 40-41)	Analysis of supply chain complexity.	SC	Automotive / Engineering / Electrical / Chemical / Telecommunication / Life Sciences / Consumer Goods	Europe	06/2004 - 10/2004	45 (back - - -)	45					
Wu, Frizelle and Efstathiou (2007, pp. 217-218, 222-223)	Identification and analysis of the relationship between costs and supply chain complexity indices.	SC	Engineering / Chemical	UK	- - -		X		2	X		
Abdelkafi (2008, pp. 228-230, 305-314)	Analysis of supply chain complexity and identification of the main influencing variables.	SC	Medical Industry	Germany	- - -		X		1	X		
Bozarth *et al.* (2009, pp. 78, 83-85)	Analysis and evaluation of supply chain complexity.	SC	Engineering / Electrical / Transport	Austria, Finland, Japan, Germany, Sweden, USA, South Korea	2005 - 2007	4,807 (back - - -)						
Carbonara and Giannoccaro (2009, p. 553)	Evaluation of supply chain complexity by measuring a set of supply chain features.	SC	Furniture Industry / Clothing & Textile	Italy	- - -	X	X		2		X	
Caridi, Pero and Sianesi (2009, pp. 388-389)	Analysis of the question how innovations affect supply chain management decisions and supply chain complexity.	SC	Automotive / Furniture Industry / Tractor / Household Appliances / Aircraft / Medical Industry	Italy	- - -	X	X		20		X	
Klagge and Blank (2012, p. 2)	Analysis of supply chain complexity and identification of the complexity drivers.	SC	- - -	Germany	2011		40					
Manuj and Sahin (2011, pp. 513-516)	Analysis of the supply chain and the supply chain decision-making complexity.	SC	- - -	- - -	- - -		11					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part I)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	**Research objectives**	**Focus**	**Field(s) of industry**	**Region/ Country**	**Research's period** (mm/yyyy)	**Applied data collection method, sample size and amount of received data**						
						Questionnaire	**Expert interviews**	**Workshop(s)**	**Case study**	**Observation**	**Documentary analysis**	**Not specified**
Alflayyeh (2013, pp. 60-98)	Investigation of the question how companies can manage complexity's challenges through effective network practices and how supply chain complexity can be measured.	SC	Engineering / Service Industry	USA	- - -	1,500 (back 193)						
Gerschberger and Hohensinn (2013, pp. 1-2)	Analysis of the development of supply chain complexity within the 4 perspectives market, process, product and organization.	SC	Engineering	Austria	- - -		24	1	1			
Leeuw, Grotenhuis and Goor (2013, pp. 969-974)	Identification of complexity drivers in the supply chain.	SC	Wholesale	Netherlands	- - -	X	X		5			
Subramanian and Rahman (2014, pp. 17-23)	Analysis of supply chain complexity and development of appropriate supply chain strategies based on material flow and contractual relationships.	SC	Automotive	Worldwide	- - -				1			
Brandon-Jones, Squire and Rossenberg (2015, pp. 6903-6908)	Analysis of the dimensions regarding supply base complexity, the effects and its management.	SC	Engineering	UK	- - -	1,200 (back 264)						
Subramanian, Rahman and Abdulrahman (2015, pp. 269, 275-279, 282)	Identification of tangible and intangible factors regarding sourcing complexity and investigation of the question how well the companies currently handle those elements.	SC	Automotive / Electrical / Metal / Plastics / Papers / Textile	China	10/2011 - 05/2012	600 (back 101)						
Haumann *et al.* (2012, pp. 108-111)	Identification and evaluation of complexity drivers and their influences in the field of remanufacturing.	R	- - -	- - -	- - -		X					

Table 15: Overview about empirical researches in the field of complexity management between 1999 and 2015 (Part J)

Explanation according to focus and occurrence in literature:

G	General in manufacturing companies	(N: 32)
PD	Product development	(N: 6)
PR	Production	(N: 3)
L	Logistics	(N: 5)
OPD	Order Processing/Distribution/Sale	(N: 4)
SC	Internal Supply Chain	(N: 16)
R	Remanufacturing	(N: 2)
OF	Other fields	(N: 4)

Explanation according to field(s) of industry, region/country, research's period and sample size:

- - -	No information referred
X	Applied, but no sample size is referred
X X	No data collection method and sample size referred

Author(s)	Research objectives	Focus	Field(s) of industry	Region/ Country	Research's period (mm/yyyy)	Applied data collection method, sample size and amount of received data: Questionnaire	Expert interviews	Workshop(s)	Case study	Observation	Documentary analysis	Not specified
Seifert *et al.* (2013, pp. 647-649)	Identification and evaluation of complexity drivers and their influences in the field remanufacturing.	R	- - -	- - -	- - -	X	X	X			X	
Blockus (2010, pp. 191-268, 330-353)	Analysis of complexity in the service industry.	OF	Banking / Insurance / Telecommunication	Switzerland	- - -		21		6			
He *et al.* (2012, pp. 1781-1782)	Evaluation of project complexity by identifying the key factors.	OF	- - -	- - -	- - -	X	X					
Maturity (2015)	Examination of an effective model based on internal service complexity.	OF	- - -	Germany	Summer 2014	946 (back 710)						
Braun (2016, pp. 232-284)	Analysis of management's perception regarding information technology complexity.	OF	Automotive / Engineering / Electrical / Chemical & Pharmaceutical / Food / Finance & Insurance / Building Industry / Biotechnology / Medical Industry / Information Technology / Consumer Goods / Transport & Logistics / Administration & Civil Service	Europe	May 2015							X X

During our literature analysis, we identified 13 different empirical studies, which are focused on complexity drivers in the fields general in manufacturing companies (N: 3), production (N: 2), logistics (N: 2), order processing/distribution/sale (N: 2), internal supply chain (N: 2) and remanufacturing (N: 2). However, no empirical study regarding complexity drivers and their effects in product development exists in literature. Table 15 shows that previous empirical studies regarding product development have been done by the following 6 authors: Li *et al.* (2005, pp. 2577-2579, 2583-2584), Kim and Wilemon (2009, pp. 547-550; 2012, pp. 1, 4-6), Newman (2009, p. 2), Chronéer and Bergquist (2012, pp. 21, 24-26) and Grussenmeyer and Blecker (2013, p. 140). The empirical studies were conducted in different countries and fields of industry between the time period 2005 and 2013. In these studies, the authors pursued also different objectives.

In their empirical study, Li *et al.* (2005, pp. 2577-2579, 2583-2584) analyzed the impact of environmental complexity on the choice of management control systems and their effects on product development and process decisions. The study was conducted in China in the year 2002 by using questionnaires and comprises 9 different fields of industry: Engineering, electrical, metal & materials, chemical & pharmaceutical, food, clothing & textile, telecommunication, commercial products and other fields of industry.

Kim and Wilemon (2009, pp. 547-550; 2012, pp. 1, 4-6) published 2 papers with results from their empirical researches. In their first study, they identified and analyzed the conditions, which cause complexity in new product development to increase the understanding of an effective complexity management. Furthermore, they identified and analyzed methods for complexity handling. The second study was done with the objective to increase the understanding of the consequences in new product development projects when complexity arises and the competitive advantages for companies, which manage complexity effectively. The 2 studies were conducted in the USA, especially in the states of New York and Connecticut and comprised 5 different fields of industry: Engineering, electrical, industrial photographic paper, medical industry, heating and ventilating, as well as air conditioning industry. In their empirical studies, the methodology expert interviews was used for data collection. No information regarding the research period was mentioned in the publications and no complexity drivers were identified.

Newman (2009, p. 2) analyzed the complexity of a global new product development process and discussed the question how complexity can be reduced through component's standardization and modularization. The study was done by using expert interviews. Regarding research period, field of industry and region, no information was given.

Chronéer and Bergquist (2012, pp. 21, 24-26) identified and analyzed the complexity regarding research and development projects. The study was conducted in Sweden and comprised 6 different fields of industry: Metal, rubber & plastics, chemical, papers, mining, as well as food & dairy. For data collection, they combined the 3 methodologies expert interviews, case studies and observations. No information regarding the research period was mentioned in literature.

Another empirical study in the field of product development was done by Grussenmeyer and Blecker (2013, p. 140). The study was conducted in Germany and Italy in the year 2011. The objective of their study was the analysis of project's complexity level in new product development and the evaluation of a specific complexity management in product development. In their research, Grussenmeyer and Blecker (2013, p. 140) used questionnaires for data collection. Regarding the fields of industry, no information was mentioned in literature.

Table 16 summarizes the results of our analysis regarding to the previous empirical researches concerned with complexity management in the field product development. The table shows a list of currently existing empirical studies and gives an overview of their specific research period, region, fields of industry and applied data collection methodologies. Furthermore, the existing empirical studies are analyzed and evaluated in comparison to the objectives of our empirical study regarding complexity management in product development. The evaluation is based on the following 3 criteria: Fulfilled (+ +), partially fulfilled (+) and not fulfilled (-).

Table 16: List of existing empirical researches focused on product development and their content

Content		**Author(s)**					
		Li *et al.* (2005, pp. 2577-2579, 2583-2584)	Kim and Wilemon (2009, pp. 547-550)	Newman (2009, p. 2)	Chronéer and Bergquist (2012, pp. 21, 24-26)	Kim and Wilemon (2012, pp. 1, 4-6)	Grussenmeyer and Blecker (2013, p. 140)
Research period		2002	- - -	- - -	- - -	- - -	2011
Region/Country		China	USA	- - -	Sweden	USA	Germany, Italy
Fields of Industry	Automotive						
	Engineering	•	•			•	
	Electrical & Optics	•	•			•	
	Metal	•			•		
	Petroleum & Plastics				•		
	Chemical & Pharmaceutical	•			•		
	Glas, Ceramic, Pit & Quarry				•		
	Food, Forage & Tobacco	•			•		
	Lumber, Papers, Printing & Furniture		•		•	•	
	Clothing & Textile	•					
	Others	•	•			•	
Data collection methodology	Questionnaire	•					•
	Expert interviews		•	•	•	•	
	Workshop(s)						
	Case study				•		
	Observation				•		
	Documentary analysis			•			
Main research objectives	Complexity driver's identification and analysis	-	+	-	-	-	-
	Identification and analysis of complexity driver's effects	-	-	-	-	-	-

Evaluation criteria:

fulfilled	(+ +)	Specific complexity drivers and their effects are described in detail.
partially fulfilled	(+)	Complexity drivers and their effects are only mentioned, but not described in detail.
not fulfilled	(-)	No information regarding complexity drivers and their effects is referred to.

Analyzing the existing empirical studies regarding complexity in product development (see Table 16), as well as other fields (e.g. general in manufacturing companies, production, logistics, etc.), we come to the conclusion that no empirical research, focused on complexity management in product development in manufacturing companies in Germany, including the identification and analysis of complexity drivers and their effects, exists yet. By presenting a systematic, explicit and reproducible empirical research regarding product development in manufacturing companies in Germany, we want to close the aforementioned literature gap.

4.3 Empirical research

4.3.1 Research methodology and objectives

In this empirical research, we followed the methodology of Flynn *et al.* (1990, pp. 253-255). Based on social sciences, Flynn *et al.* (1990, pp. 253-255) developed a 6-stage systematic approach for conducting an empirical research (see Figure 11). This helps the researcher to describe, what happens in the real world (Moody, 2002, p. 1). The approach starts with the determination of the theoretical foundation (stage I) and the research design, which is applied to the research problem and the theoretical foundation (stage II). In stage III, the data collection method is selected. Data collection is an important part of an empirical research (Jasti and Kodali, 2014, p. 1093). Several methods are described in literature and can be combined for better results (Flynn *et al.*, 1990, pp. 258-259; Jasti and Kodali, 2014, pp. 1093-1097). The data collection method, which is mostly used, is the questionnaire. It is a useful technique for single and multiple case studies, as well as panel studies and focus groups. Next, the sample description for research's implementation is defined and the data is collected in stage IV. Before preparing the research report for publication (stage VI), the collected data is processed and analyzed in stage V (Flynn *et al.*, 1990, pp. 253-268).

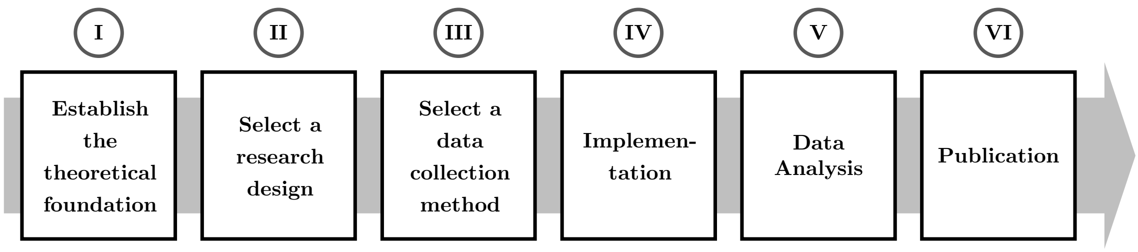


Figure 11: Six stage systematic approach for empirical research, developed by Flynn *et al.*

The first step in performing an empirical research is to define the research questions and objectives. Empirical research can be used to document the state-of-the-art in different fields of research (Flynn *et al.*, 1990, pp. 250, 253-254). In this research, we use an empirical study to document the current state in practice regarding the complexity drivers and their effects in the field of product development in the manufacturing industry of Germany. A further objective is to compare literature findings with the results from our empirical research to identify commonalities and differences.

Based on our introduction, the literature review and the identified research gap, we determined 4 further research questions, focused on our empiricism (called empirical research questions) to close the research gap:

- RQ 3: How is the product development of the participating companies characterized regarding product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; the height of the own value adding percentage, as well as organization's influence on product development's complexity?
- RQ 4: What are the main complexity drivers in product development and what interdependencies exist between them? Can the complexity drivers be aggregated to factors?
- RQ 5: What influences do high complexity and especially the complexity drivers have on product development's complexity?
- RQ 6: What are the significant differences and commonalities between the literature and practical (empirical) results?

Regarding the limitations of our research approach, we decided to limit the scope of our empirical research by analyzing only the German manufacturing industry, because the German manufacturing industry and its product development is one of the most leading industries in the world, compared to other countries and/or fields of industry. Furthermore, by our limitation we want to ensure that this research is manageable. In addition, we had only data from the German manufacturing industry available for our empirical research. Data from other countries and/or fields of industry was not available at the time our research was conducted.

4.3.2 Questionnaire's design, data collection methodology, sample description and statistical analysis

The implementation of an empirical research starts with the selection of the data collection method and the sample description (Flynn *et al.*, 1990, pp. 256-263). For data collection, a standardized questionnaire with 15 questions and a fixed response possibility was applied in this research, because the questionnaire is the most used data collection method in scientific research and provides the best results regarding reliability, validity and generalization (Flynn *et al.*, 1990, p. 259).

The data was collected from a stratified random sample. The sample was taken out of a given population of 17,862 manufacturing companies, located in Germany with more than 50 employees. The research was conducted in 2015 and 2016. At the beginning of our empirical study in 2015, the population of 17,862 manufacturing companies was determined based on the Amadeus database. In the Amadeus database, all manufacturing companies of Germany are documented. In our research, we selected only companies with more than 50 employees, because the complexity phenomenon primarily occurs in bigger companies rather than in smaller.

As already mentioned, we used a standardized questionnaire for data collection. The questionnaire was sent in 2 stages by e-mail to 3,086 companies, exclusive of service and printing companies. According to Mayer (2013, pp. 65-68), we used a 2-stage empirical research to increase the amount of responded questionnaires and thus the research's quality. To increase answer's significance, the companies were asked in the cover letter to send the questionnaire to an experienced employee from the product development department. However, this is no guarantee that the questionnaire is send to the right person within the company and/or product development department. In this research, we assume that the responded questionnaires were answered by the right persons. All participants were assured that only aggregated data would be presented. The stratified random sample size (n = 1,565) is calculated based on the methodology of Mayer (2013, p. 66) and Raab, Poost and Eichhorn (2009, p. 84). The input parameters are the population (N = 17,862), a safety factor (t = 2), the proportion of the elements within the random sample, which fulfills the feature characteristic (p = 0.5) and the sampling error (d = 0.05). The population comprises the amount of documented companies in the Amadeus database and the safety factor depends on respondents' level of significance.

For questionnaire's design, questions with the same focus are clustered in main categories to increase understanding and transparency (Kromrey, 2009, pp. 371-386). The questionnaire in this study was structured in 3 main parts: General information regarding the respondents (company size, field of industry and respondent's position in the company), general information about product development's characteristics (dimension of product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; as well as the height of the own value adding percentage) and information about the complexity drivers and their effects.

The questions were formulated based on the research questions. To ensure representative results, the questions must be formulated explicit and easily (Kromrey, 2009, pp. 371-375). In the questionnaire, the scale items were designed as statements and the interviewees were asked about their assessment. For measurement, we used nominal scales (yes/no) and ordinal scales (1 - no influence; 2 - small influence; ...; 5 - strong influence; 6 - very strong influence) to increase reliability, validity and comparability. Other scale items, such as interval or rational were not used in this research, because these scales have another focus and are not applicable in this research.

Before starting the empirical research, a first version of the questionnaire was pretested to identify and remove systematic gaps and inconsistencies (Hug and Poscheschnik, 2010, p. 119). In 2014, our questionnaire was pretested by 40 experts from the potential target group. The objective was to check and refine the wording, understanding, relevance, as well as the measurement instrument. Furthermore, the questionnaire length and the time for questionnaire's responding was checked. Based on pretest's results and comments from the experts, the questionnaire was revised and checked again by a smaller group of experts.

According to Flynn *et al.* (1990, pp. 264-267) and Moody (2002, p. 3), a questionnaire has to be analyzed by using statistical methods. Several data analysis techniques or statistical tests for statistical analysis exist in scientific literature and can be used by a researcher, although there is no general rule to select a particular approach (Madu, 1998, p. 354). Montoya-Weiss and Calantone (1994, p. 404) classified the data analysis techniques into 4 groups: Descriptive statistics (e.g. means, frequencies and proportions) tests of differences or similarities (e.g. t-test) measures of dimensionalities (e.g. factor analysis) and statistical interpretation of parameters (e.g. correlation analysis). For answering the empirical research questions, we analyzed the empirical findings by using the data analysis techniques from the groups descriptive statistics, measures of dimensionalities and statistical interpretation of parameters. The group tests of differences or similarities was not applied in this research, because the data analysis techniques from this group are used for testing hypotheses. Since we did not propose hypotheses or did an experiment in our research, we did not use these data analysis techniques.

4.4 Analysis of empirical research and findings

4.4.1 Sample results and data validation

For data collection, 3,086 manufacturing companies with more than 50 employees, located in Germany, were questioned. The questionnaire was sent by e-mail to them. The Amadeus database lists mostly general email-addresses of companies. Therefore, the inquiry emails sent to those addresses included the request to forward the email to an experienced employee in the department of product development.

Next, the net sample size was calculated by reducing the total sample size based on the amount of e-mails that were undeliverable or rejected by the companies. The net sample size is needed for response rate's counting (Gießmann, 2010, pp. 89-90). In our research, the final sample size consisted of 2,817 companies. In total, 295 questionnaires were answered completely and resulted in a response rate of 10.5%, which is an acceptable response rate according to Meffert (1992, p. 202). Industry's range contained 11 different fields of industry. According to their characteristics, the identified industry branches were clustered in 4 industry clusters: Technical industries, resource industries, consumer goods industry and others. The technical industry is the largest industry cluster and comprises about 60% of the respondents: Engineering (30.5%), metal (10.5%), electrical and optics (9.8%) and automotive (8.1%) (see Figure 12). Based on the Amadeus database, the technical industry is traditionally Germany's major field of industry with a percentage of 63.5%. For result's validation, the percentage of the empirical research was compared with the percentage of the database to identify commonalities and differences. In our research, the percentage of empirical research and database are very close in all industry clusters. The empirical findings are therefore representative and can be generalized.

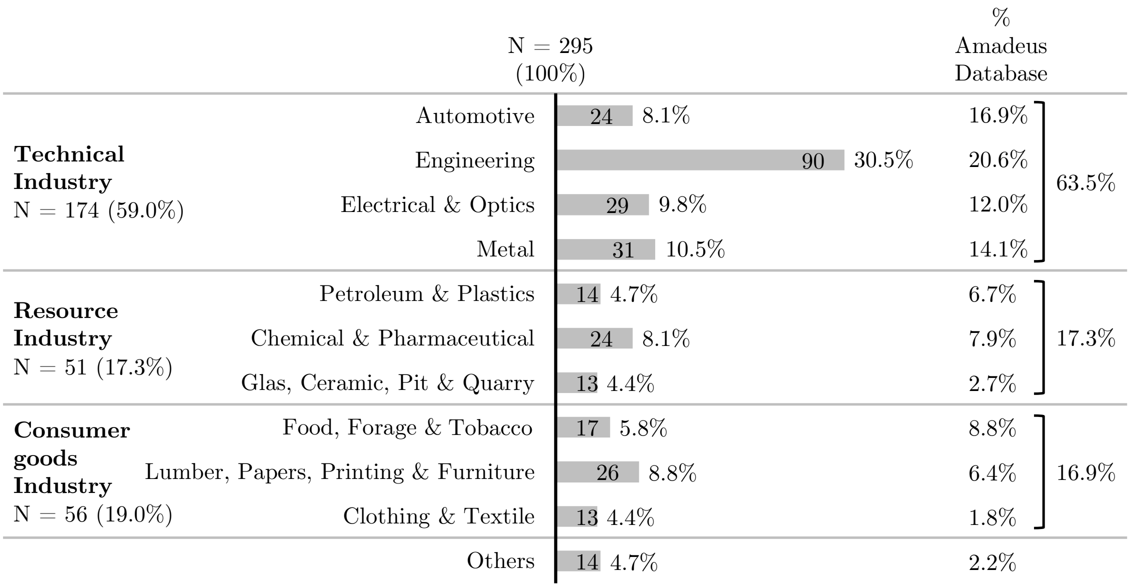


Figure 12: Frequency of received questionnaires according to industry and comparison of results and database's percentage

In the next step, the number of employees and the position profile of the respondents were analyzed (see Figure 13). With 61.8%, the small and middle-sized companies formed the biggest group in our empirical research. Larger companies with more than 250 employees represented 38.2%. Based on these results, it can be concluded that small and middle-sized companies are highly interested in empirical studies regarding complexity management and especially in product development.

The analysis of the respondent's position profile shows that 80% of the respondents can be assigned to the category upper management (see Figure 13). This category comprises the following 3 groups: Presidents, CEOs and COOs (18.0%), directors and division managers (26.1%), as well as senior managers and department managers (35.9%). This result shows that complexity in product development is an important issue for company's management.

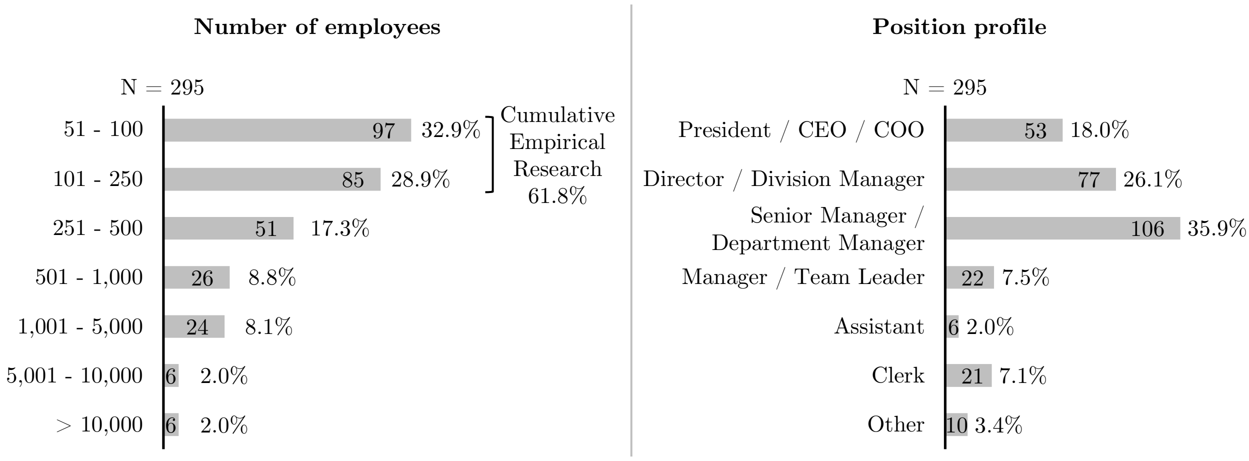


Figure 13: Overview about the number of employees and the position profile of the respondents

To answer **RQ3** and for analyzing the product development characteristics in general of the participating companies, we requested the following properties in 10 different questions (Q4 to Q13): Dimensions of product range and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and process; height of the own value adding percentage and organization's influence on product development's complexity. The results are described in Figure 14.

Approximately 75% of the companies are characterized by a medium and big product (Q4) and variant range (Q5). Based on the analysis of questions 6 and 7, more than 50% of the developed products have a life cycle length of more than 72 months (Q6), but approximately 70% of the respondents specified that the length of product development process is less than 25 months (Q7). Furthermore, the majority of companies indicate that their products consist of many different components (Q8), materials (Q9), as well as technologies (Q10) and the product development process consists of many different processes (Q11). Furthermore, the percentage of the own value adding activity in product development was analyzed. However, there was no explicit tendency recognizable (Q12). In literature, organizational complexity and value-added complexity are general complexity drivers in the company (Vogel and Lasch, 2016, pp. 27-32). To analyze organization's influence on product development's complexity, the respondents were questioned about their evaluation. More than 75% of the respondents specified that the organization has no negative influence on product development's complexity (Q13). Comparing this result with literature, there is a discrepancy, especially regarding the complexity drivers in product development, which are described in subsection 4.2.2. In literature, 9 authors describe 28 different organizational complexity drivers, which are responsible for increasing complexity in the company and especially in product development. It would be interesting to investigate the reasons for this discrepancy wihin a further empirical research (e.g. investigation through expert interviews).

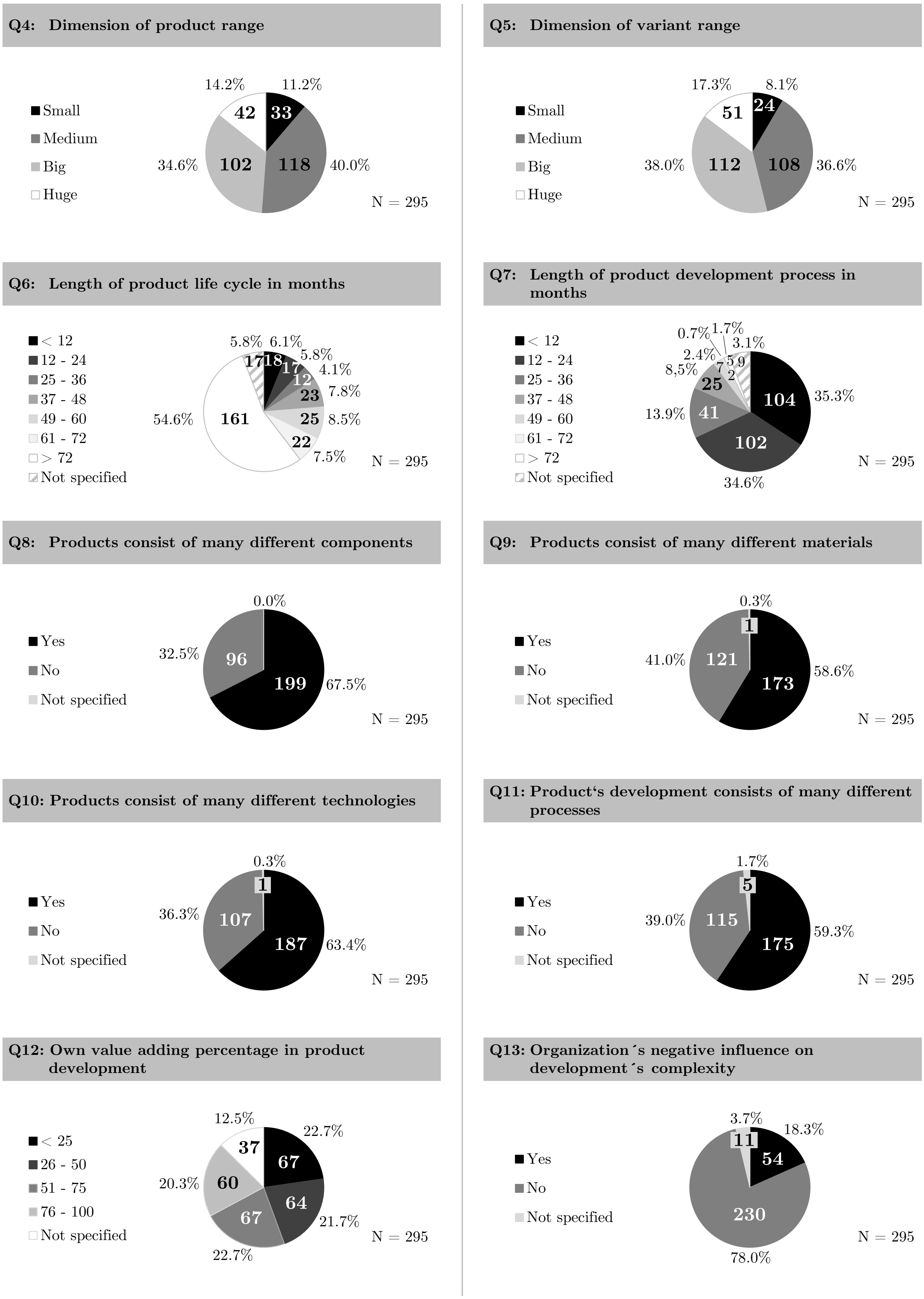


Figure 14: Analysis results regarding the product development characteristics of the participating companies

4.4.2 Complexity drivers and their effects on company's complexity

We started our pretest by using the complexity drivers in product development, which are already mentioned in literature and published before 2015 (N: 72) (see subsection 4.2.2). Furthermore, we added additional complexity drivers from other fields along the value chain to extend the amount of complexity drivers in total, because product development has an influence on all parts of the value chain (N: 44). The complexity drivers originate in the following fields: General in manufacturing companies (Bliss, 1998, pp. 146-148; Bliss, 2000, pp. 4-7; Schoeneberg, 2014a, pp. 16-19), procurement and purchasing (Gießmann and Lasch, 2010, pp. 159-167), logistics (Gießmann, 2010, pp. 36-38; Lasch and Gießmann, 2009a, pp. 200-202), production (ElMaraghy *et al.* 2012, pp. 793-794; Schöttl *et al.*, 2014, pp. 259-260), order processing, distribution and sales (Buob, 2010, pp. 18-20), as well as internal supply chain (Serdarasan, 2011, p. 794) and remanufacturing (Haumann *et al.*, 2012, pp. 107-109, 111). In total, the collection of the complexity drivers, used in our pretest, comprises 116 different complexity drivers. One of the objectives of doing the pretest was to ask the experts about the relevance of the different complexity drivers, because we wanted to reduce the number of drivers for the final questionnaire to the truly relevant drivers. As a result of our pretest, from the expert's view, only 59 complexity drivers of the total amount of 116 are relevant and should be used in the final questionnaire and empirical research. Furthermore, they mentioned additional important and relevant complexity drivers that we added to our questionnaire (N: 5). The final questionnaire comprises 64 complexity drivers in total. Another surprising result is that the internal complexity drivers product complexity (general), product portfolio complexity (general), technological complexity (general) and development complexity (general) are not relevant from expert's view, although these drivers are fundamentally connected to the product development process (see Table 17). One reason is that these drivers are general drivers and are already known and handled by the experts. Another reason is that the experts want to have some further information about specific complexity drivers, which are important for complexity management in product development. Thus, these general drivers do not need further analysis. Table 17 presents an overview about the different complexity drivers, which are mentioned in literature in product development and the other fields along the value chain, as well as the results of expert's evaluation regarding the relevance of the different drivers.

Answering the forth research question, we used different statistical methods for analyzing questionnaire's results. The main complexity drivers in product development in each driver category were identified by using descriptive statistics. In this research, 64 different complexity drivers were evaluated by the respondents within an ordinal scale (1 - no influence; 2 - small influence;...; 5 - strong influence; 6 - very strong influence) according to their influence on product development's complexity. The complexity drivers, which are evaluated by more than 50% of the respondents with a strong or very strong influence on product development's complexity are identified as the main complexity drivers. As already mentioned, 64 complexity drivers were included in the questionnaire, but only 30 drivers were regarded by the respondents in different fields of industry as drivers that have a strong or very strong influence in principle (see Table 17, reference No. 4 in the field explanation). Table 17 presents the identified main complexity drivers in product development in the different fields of industry, which are identified in our empirical research. As a result of our research, some industries are influenced by more complexity drivers than other industries. For example, the following fields of industry are influenced by 12 main complexity drivers: Automotive, petroleum & plastics, as well as food, forage & tobacco.

In contrast, the electrical & optics industry or the chemical & pharmaceutical industry are influenced by only 6 drivers.

A further result of our empirical research is that some complexity drivers are more important than other drivers, because these drivers occur in most fields of industry. These include the following complexity drivers: Market's economic factors, individuality of customer demands, number and strength of competitors, product range/portfolio and amount of simultaneous projects. The driver variety of customer requirements influences every field of industry (see Table 17). Furthermore, product development's complexity is influenced to the same extend by external, as well as internal complexity drivers (14 external drivers vs. 16 internal drivers). Comparing this result with literature (see subsection 4.2.2), most of the described complexity drivers in literature belong to the main category internal complexity drivers (28 external drivers vs. 79 internal drivers). Thus, there is also a discrepancy between literature and practice. These results draw to the conclusion that internal complexity drivers can be handled by the company itself so they are not considered as problems, whereas external complexity drivers cannot be handled easily and are therefore regarded more as problems. Thus, less internal complexity drivers are described by the respondents in our research as drivers with a high influence than it would be expected when looking at the findings in literature.

As also seen in Table 17, the different fields of industry are influenced by individual main complexity drivers. The technical industries are characterized by 6 main complexity drivers: Market's economic factors, variety of customer requirements, individuality of customer demands, number and strength of competitors, product range/portfolio and amount of simultaneous projects. The resource industries and the consumer goods industry are also characterized by variety of customer requirement and individuality of customer demands. Furthermore, the resource industries are influenced by the 3 complexity drivers political framework conditions, demand's dynamics, as well as technological progress and the consumer goods industry is characterized by market's economic factors, number and strength of competitors, as well as product range/portfolio.

In summary, the external complexity driver categories general market-related complexity, demand complexity and competitive complexity and their specific drivers are most important for complexity management in product development. In contrast, the complexity drivers from the categories society complexity, technological complexity (external and internal), supply complexity, target complexity, customer complexity, product and product portfolio complexity, product development complexity, organizational complexity, production complexity, process complexity, planning, control and information complexity, as well as logistics complexity, sales and distribution complexity and the general complexity drivers have mostly no strong or very strong influence on product development's complexity and do not seem to be so important for complexity management in product development.

It was surprising that the complexity driver categories technological complexity (external and internal), product and product portfolio complexity, as well as product development complexity and their specific drivers did not have a strong or very strong influence on product development's complexity in total, although product development is characterized by these categories.

The comparison between literature's complexity drivers and the complexity drivers identified in this empirical research is shown in subsection 4.4.3.

Table 17: Overview about the complexity drivers, which are evaluated by the respondents with a strong and very strong influence on product development (Part A)

Explanation:

1 Complexity drivers, which are documented in the literature review, focused on product development (see subsection 4.2.2) (N: 72)

2 Complexity drivers, which are documented in literature in other fields along the value chain and general in manufacturing companies (N: 44)

3 Additional complexity drivers, mentioned by the practice during expert interviews (N: 5)

4 Complexity drivers, which were regarded by the respondents as drivers that have a strong or very strong influence (N: 30)

RfQ Relevant (R) for questionnaire based on the results of our pretest and several expert interviews (N: 64)

			Fields of Industry											
			Technical Industry				Resource Industry			Consumer goods Industry				
Origin	**Specific complexity drivers in each category**	**RfQ**	Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	Others	**Total**
External complexity	**Society complexity**													
	Environmental complexity (general) [1]													
	Value change & value awareness [1, 4]	R					•							**1**
	Environmental awareness in population [2]	R												
	Ecological conditions/factors [1]	R												
	Political framework conditions [1, 4]	R					•		•					**2**
	Legal factors [1, 4]	R						•		•			•	**3**
	Change of populations structure [1]													
	Standards and regulations [1]													
	Turbulences in company's environment [1]													
	Interdependencies between environmental factors [1]													
	General market-related complexity													
	Market complexity (general) [1]													
	Market's infrastructure [3]	R												
	Market's economic factors [2, 4]	R	•	•	•	•	•				•	•		**7**
	Variety of customer requirements [2, 4]	R	•	•	•	•	•	•	•	•	•	•	•	**11**
	Market's change [1, 4]	R	•			•						•		**3**
	Market's globalization [1, 4]	R	•	•			•					•	•	**5**
	Market's dynamics [1]													
	Market's protectionism [1]													
	Demand complexity													
	Demand complexity (general) [1]													
	Individuality of customer demands [1, 4]	R	•	•	•		•		•	•	•	•	•	**9**
	Demand's dynamics [2, 4]	R					•		•	•		•	•	**5**
	Competitive complexity													
	Competitive complexity (general) [1]													
	Number and strength of competitors [1, 4]	R	•	•	•	•			•	•		•	•	**8**
	Competitor's dynamics [2, 4]	R						•		•			•	**3**
	Competitive pressure [1]													

Table 17: Overview about the complexity drivers, which are evaluated by the respondents with a strong and very strong influence on product development (Part B)

Explanation:

1 Complexity drivers, which are documented in the literature review, focused on product development (see subsection 4.2.2) (N: 72)

2 Complexity drivers, which are documented in literature in other fields along the value chain and general in manufacturing companies (N: 44)

3 Additional complexity drivers, mentioned by the practice during expert interviews (N: 5)

4 Complexity drivers, which were regarded by the respondents as drivers that have a strong or very strong influence (N: 30)

RfQ Relevant (R) for questionnaire based on the results of our pretest and several expert interviews (N: 64)

			Fields of Industry											
			Technical Industry				Resource Industry			Consumer goods Industry				
Origin	**Specific complexity drivers in each category**	**RfQ**	Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	Others	**Total**
External complexity	**Technological complexity (external)**													
	External technological complexity (general) [1]													
	Technological progress [1, 4]	R	•				•	•	•				•	**5**
	Technological innovations & availability [1, 4]	R											•	**1**
	New technologies and materials [1]													
	Supply complexity													
	Variety of supplied goods [2]	R												
	Amount of suppliers [2]	R												
	Supply strategy or concept [2, 4]	R											•	**1**
	Quality uncertainty of delivered goods [2]	R												
	Uncertainty of delivery date [2]	R												
		Total:	**7**	**5**	**4**	**4**	**8**	**4**	**6**	**6**	**3**	**7**	**10**	
Internal correlated complexity	**Target complexity**													
	Target complexity (general) [1]													
	Amount of different targets [1]	R												
	Business objective's change frequency [2]	R												
	Business objective's time pattern [2]	R												
	Customer complexity													
	Customer's amount [2, 4]	R											•	**1**
	Customer structure [1, 4]	R					•						•	**2**
	Customer's participation [2, 4]	R	•			•								**2**
	Product & product portfolio complexity (Part A)													
	Product complexity (general) [1]													
	Product portfolio complexity (general) [1]													
	Product variety [1, 2, 4]	R							•				•	**2**
	Product range/portfolio [1, 4]	R	•	•	•		•			•	•			**6**
	Product portfolio change frequency [2]	R												
	New product launch's frequency [2]	R												
	Product life cycle length [2]	R												
	Product structure/design [1]	R												
	Product technology [1, 2]													

Table 17: Overview about the complexity drivers, which are evaluated by the respondents with a strong and very strong influence on product development (Part C)

Explanation:

1 Complexity drivers, which are documented in the literature review, focused on product development (see subsection 4.2.2) (N: 72)

2 Complexity drivers, which are documented in literature in other fields along the value chain and general in manufacturing companies (N: 44)

3 Additional complexity drivers, mentioned by the practice during expert interviews (N: 5)

4 Complexity drivers, which were regarded by the respondents as drivers that have a strong or very strong influence (N: 30)

RfQ Relevant (R) for questionnaire based on the results of our pretest and several expert interviews (N: 64)

			Fields of Industry											
			Technical Industry				Resource Industry			Consumer goods Industry				
Origin	**Specific complexity drivers in each category**	**RfQ**	Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	Others	**Total**
Internal correlated complexity	**Product & product portfolio complexity (Part B)**													
	Component type [1]													
	Variety of parts and modules [1]	R												
	Variety of the applied materials [1]	R												
	Variance in product design [2]	R												
	Availability of materials or components [3]	R												
	Properties of modules or materials [1, 4]	R					•			•				**2**
	Product's degree of innovation [2, 4]	R	•					•		•				**3**
	Product life cycle length [2, 4]	R	•											**1**
	Technological complexity (internal)													
	Technology complexity (general) [1]													
	Technology change/innovation [1]	R												
	Number of different applied technologies [1]	R												
	Hardware and software complexity (general) [1]													
	Type of data medium [1]													
	Size of data medium [1]													
	Type of interfaces [1]													
	Amount of interfaces [1]													
	Criteria of hardware and software tests [1]													
	Technology's complicacy [3]	R												
	Technology's combination [2]	R												
	Technology life cycle length [2]	R												
	Product development complexity													
	Development complexity (general) [1]													
	Development program's complexity [1]													
	Applied methods or instruments [1]													
	Product software [2, 4]	R		•										**1**
	Data processing system [2]	R												
		Total:	**4**	**2**	**1**	**1**	**3**	**1**	**1**	**3**	**1**	**0**	**3**	

Table 17: Overview about the complexity drivers, which are evaluated by the respondents with a strong and very strong influence on product development (Part D)

Explanation:

1 Complexity drivers, which are documented in the literature review, focused on product development (see subsection 4.2.2) (N: 72)

2 Complexity drivers, which are documented in literature in other fields along the value chain and general in manufacturing companies (N: 44)

3 Additional complexity drivers, mentioned by the practice during expert interviews (N: 5)

4 Complexity drivers, which were regarded by the respondents as drivers that have a strong or very strong influence (N: 30)

RfQ Relevant (R) for questionnaire based on the results of our pretest and several expert interviews (N: 64)

			Fields of Industry: Technical Industry				Resource Industry			Consumer goods Industry				
Origin	**Specific complexity drivers in each category**	**RfQ**	Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	Others	**Total**
Internal autonomous complexity	**Organizational complexity**													
	Organizational complexity (general) [1]													
	Organization's structure [1]													
	Organization's/Company's size [1]	R												
	Amount of hierarchical levels [2]	R												
	Degree of centralization [2]	R												
	Business segment/industrial sector [1]													
	Company's strategy (strategical complexity) [1, 2]													
	Complexity between cooperation partners [1]													
	Employee complexity (general) [1]													
	Amount of employees [2]	R												
	Lack of transparency (general) [1]													
	Lack of cost transparency [1]													
	Lack in consistency of activities [1]													
	Amount of simultaneous projects [3, 4]	R	•	•	•			•		•			•	**6**
	Amount of simultaneous processes [3]	R												
	Production complexity													
	Production complexity (general) [1]													
	Vertical range of manufacture [2]	R												
	Production system [2, 4]	R											•	**1**
	Production structure [1]													
	Manufacturing technology [1]													
	Maintenance complexity (general) [1]													
	Process complexity													
	Process complexity (general) [1]													
	Variety of processes [1, 2, 4]	R							•					**1**
	Amount of process interfaces [2]	R												
	Process degree of cross-linking [2, 4]	R											•	**1**
	Process standardization [2, 4]	R											•	**1**

Table 17: Overview about the complexity drivers, which are evaluated by the respondents with a strong and very strong influence on product development (Part E)

Explanation:
1 Complexity drivers, which are documented in the literature review, focused on product development (see subsection 4.2.2) (N: 72)

2 Complexity drivers, which are documented in literature in other fields along the value chain and general in manufacturing companies (N: 44)

3 Additional complexity drivers, mentioned by the practice during expert interviews (N: 5)

4 Complexity drivers, which were regarded by the respondents as drivers that have a strong or very strong influence (N: 30)

RfQ Relevant (R) for questionnaire based on the results of our pretest and several expert interviews (N: 64)

			Fields of Industry											
			Technical Industry				Resource Industry			Consumer goods Industry				
Origin	**Specific complexity drivers in each category**	**RfQ**	Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	Others	**Total**
Internal autonomous complexity	**Planning, control and information complexity**													
	Planning, control & information complexity (general) [1, 2]													
	Lack in strategic planning [1]													
	Organization's information technology systems [1]													
	Information flow's variety [2, 4]	R								•			•	**2**
	Information flow's dynamics [2, 4]	R					•			•				**2**
	Requirements of company's control [2]	R												
	Company's control level of detail [2]	R												
	Company's communication system [2]	R												
	Logistics complexity													
	Supply chain complexity (general) [1, 2]													
	Sales and distribution complexity													
	Distribution complexity (general) [1]													
	Marketing complexity (general) [1]													
		Total:	**1**	**1**	**1**	**0**	**1**	**1**	**1**	**3**	**0**	**0**	**5**	
General complexity	Variety/Multiplicity [1]													
	Dynamics [1]													
		Total:	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	

Next, a correlation analysis was conducted to test the bivariate relationships and interdependencies between the 64 different complexity drivers. The results are documented in the appendix (see Table 49). Based on the correlation analysis, 29 strong (correlation coefficient $0.6 < x \leq 0.8$) and 3 very strong correlations (correlation coefficient $0.8 < x \leq 1.0$) were identified and clustered according to their origin and the literature's main complexity driver categories (see Table 18). Strong correlations between different complexity drivers occur in the following categories: Society complexity, demand complexity, general market-related complexity, technological complexity (external and internal), supply complexity, target complexity, customer complexity, product and product portfolio complexity, product development complexity, production complexity, process complexity, as well as planning, control and information complexity and organizational complexity. Beyond, in the 2 categories process complexity and planning, control and information complexity, very strong correlations occur between the different complexity drivers process degree of cross-linking and amount of process interfaces, information flow's dynamics and variety, as well as company's control level of detail and requirements of company's control. Overall, the correlation analysis provides 2,080 correlations, however 88.9% are weak correlations (correlation coefficient $0.2 < x \leq 0.4$). Only 6.5% are medium correlations (correlation coefficient $0.4 < x \leq 0.6$) and 1.4% strong correlations.

Table 18: Overview about the strong and very strong correlations between different complexity drivers

Main complexity driver category	Correlation between the specific complexity drivers			Corre-lation
Society complexity	Ecological conditions/factors	↔	Environmental awareness in population	strong
Demand complexity & General market-related complexity	Individuality of customer demands	↔	Variety of customer requirements	strong
Technological complexity (external)	Technological innovations & availability	↔	Technological progress	strong
Supply complexity	Amount of suppliers	↔	Variety of supplied goods	strong
	Supply strategy or concept	↔	Amount of suppliers	strong
	Uncertainty of delivery date	↔	Quality uncertainty of delivered goods	strong
Target complexity	Business objective's change frequency	↔	Amount of different targets	strong
Customer complexity	Customer structure	↔	Customer's amount	strong
Product & product portfolio complexity	Product variety	↔	Product range/Portfolio	strong
	New product launch's frequency	↔	Product portfolio change frequency	strong
	Variety of parts and modules	↔	Product structure/design	strong
	Variety of the applied materials	↔	Variety of parts and modules	strong
	Properties of modules and materials	↔	Availability of materials or components	strong
Technological complexity (internal)	Technology's complicacy	↔	Number of different applied technologies	strong
	Technology's combination	↔	Number of different applied technologies	strong
	Technology's combination	↔	Technology's complicacy	strong
	Technology life cycle length	↔	Technology's combination	strong
Product development complexity	Data processing system	↔	Product software	strong
Production complexity	Production system	↔	Vertical range of manufacture	strong
Process complexity	Amount of process interfaces	↔	Variety of processes	strong
	Process degree of cross-linking	↔	Variety of processes	strong
	Process standardization	↔	Process degree of cross-linking	strong
Planning, control and information complexity & Process complexity	Information flow's variety	↔	Process degree of cross-linking	strong
	Information flow's variety	↔	Process' standardization	strong
	Information flow's dynamics	↔	Process degree of cross-linking	strong
Organizational complexity	Organization's/Company's size	↔	Amount of hierarchical levels	strong
	Amount of simultaneous processes	↔	Amount of simultaneous projects	strong
Process complexity	Process degree of cross-linking	↔	Amount of process interfaces	very strong
Planning, control and information complexity	Information flow's dynamics	↔	Information flow's variety	very strong
	Company's control level of detail	↔	Requirements of company's control	very strong

Based on the correlation analysis, a factor analysis with varimax rotation was applied for complexity driver's aggregation. We used the statistic software SPSS 21 to perform the factor analysis and to list the eigenvalues associated with each linear component (factor) before extraction, after extraction and after rotation (see appendix Table 50). Before extraction, 64 linear components (factors) are identified within the data set. In this case, the amount of eigenvectors are the same as variables and so there will be as many factors as variables. The eigenvalues are associated with each factor and represent the variance, which is explained by that particular linear component (Field, 2005, pp. 632-634). In our study, factor 1 explains 25.276% of total variance. To identify the relevant amount of factors, which explains cumulative more than 50%, we extract only factors with eigenvalues greater than 2. All factors with eigenvalues of 2 and less are ignored. For optimizing the factor structure, we used the varimax rotation. As a result of our factor analysis, we identified 7 factors, reflecting the complexity drivers. The identified factors clarify 51% of the 64 complexity drivers, thus these factors are important for a company's complexity management. The first factor describes a company's complexity. Product and technology complexity load onto the second factor. The third and fourth factor reflect the customer complexity and the market complexity. Supply complexity loads onto the fifth factor. The sixth factor describes environmental and society and the seventh factor describes company's target complexity. Table 19 presents an overview about the identified factors und their factor load's ranges. Factor loadings are required for factor's interpretation. The factor loadings are described in detail in the appendix (see Table 51).

Table 19: Overview about the identified factors, factor load's range and the amount of aggregated complexity drivers

Factor	Reflecting complexity driver	% of Variance (Initial Eigenvalue)	Factor load's range	Amount of aggregated complexity drivers
#1	Company's complexity	25.276	0.76 – 0.54	15
#2	Product and technology complexity	6.021	0.67 – 0.42	16
#3	Customer's complexity	4.809	0.71 – 0.44	8
#4	Market complexity	4.375	0.69 – 0.35	9
#5	Supply complexity	3.718	0.75 – 0.66	5
#6	Environmental and society complexity	3.438	0.84 – 0.37	6
#7	Target complexity	3.397	0.69 – 0.45	5
Total:		**51.034**		**64**

For a target-oriented complexity management, the complexity drivers and their influences have to be identified. In literature, complexity drivers have a direct influence on the company and the total value chain (Schuh, 2005, pp. 8-19) and are responsible for high complexity in the company. Furthermore, they have an influence on a company's performance, especially on product development. To respond to **RQ5**, we developed a framework for identification, analysis and evaluation of the complexity effects in product development in our empirical research. The framework is developed based on the general framework, presented in Figure 10, and the different examples, which are described in literature (see subsection 4.2.2). In this research, 18 different effects on product development, which are clustered in the 4 categories time, quality, costs and flexibility, were evaluated by the respondents with an ordinal scale (1 - no effect; 2 - small effect;...; 5 - strong effect; 6 - very strong effect). The effects, which are evaluated by more than 50% of the respondents with a strong or very strong impact on product development's performance, were identified as the main effects.

Table 20 presents the identified main effects in product development, the amount of respondents in the different fields of industry (N_{resp}) and the amount of respondents of our survey that evaluated these effects as strong or very strong in the different fields of industry (N). As a result of our empirical research and based on the evaluation results in the different fields of industry, high complexity has mostly a strong or very strong effect on the following 4 attributes (see Table 20): Product development time (N: 155; 53%), adherence to deadlines in product development (N: 128; 43%), product quality (N: 95; 32%) and product development's costs in general (N: 123; 42%). High complexity has a strong effect on the development time in nearly all industry branches. Furthermore, high complexity has more effects in technical industries than in other fields of industry. The most important attributes in technical industries are product development time, adherence to deadlines in product development, product quality, product development's direct costs and product development's costs in general. In the resource industries, high complexity has a strong or very strong effect on the attributes product development time and adherence to deadlines in product development and thus these attributes are most important for complexity management. In the consumer goods industries, only 1 attribute is highly influenced by complexity and important for complexity management: Product development time.

To answer the fifth research question, a correlation analysis between the complexity drivers and the effects was conducted. Based on the results, only weak correlations were identified. Thus, the results were not taken into account.

Table 20: Overview of the identified main complexity effects in product development and in different fields of industry

Explanation: N_{resp}: Amount of respondents		**Technical Industry**				**Resource Industry**			**Consumer goods Industry**				
		Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	**Others**	**Total**
		N_{resp}: 24	N_{resp}: 90	N_{resp}: 29	N_{resp}: 31	N_{resp}: 14	N_{resp}: 24	N_{resp}: 13	N_{resp}: 17	N_{resp}: 26	N_{resp}: 13	N_{resp}: 14	N_{resp}: 295
High complexity in product development has a **strong** or **very strong** effect on...		N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
Time	product development time	15 (63%)	53 (59%)	21 (72%)	19 (61%)		14 (58%)	9 (69%)	9 (53%)	15 (58%)			155 (53%)
	adherence to deadlines in product development	13 (54%)	57 (63%)	19 (66%)	19 (61%)		12 (50%)	8 (62%)					128 (43%)
	delivery time of supplied goods	12 (50%)											12 (4%)
	time for product's validation	13 (54%)											13 (4%)
Quality	product quality	14 (58%)	45 (50%)	16 (55%)				8 (62%)	11 (65%)				94 (32%)
	process' balance												
	process planning and controlling												
	process size for quality check												
Costs	product development's direct costs	15 (63%)		15 (52%)	17 (55%)	8 (57%)				14 (54%)			69 (23%)
	product development's indirect costs	12 (50%)						7 (54%)					19 (6%)
	product development's costs in general	18 (75%)	55 (61%)	23 (79%)		10 (71%)		8 (62%)				9 (64%)	123 (42%)
	product costs	12 (50%)		15 (52%)		7 (50%)		7 (54%)			7 (54%)		48 (16%)
	coordination costs	12 (50%)											12 (4%)
	inventory costs	15 (63%)											15 (5%)
Flexi-bility	product design flexibility												
	product development process flexibility	12 (50%)											12 (4%)
	temporal flexibility on product development content	13 (54%)											13 (4%)
	resource management's flexibility										7 (54%)		7 (2%)
	Total amount of effects based on complexity:	13	4	6	3	3	2	6	2	2	2	1	14

4.4.3 Comparison between literature and empirical results

Answering the sixth research question, the empirical findings about complexity drivers in product development are compared with the literature findings to identify commonalities and differences. The objective is to confirm or to refine existing scientific knowledge or theories and to identify further research gaps.

In literature, 108 different complexity drivers in product development are described in total between 1998 and 2015 ($N_{Lit.\ T}$) (see Figure 15 and Table 14). In our research, only the complexity drivers, published before 2015, were considered ($N_{Lit.\ 1998\text{-}2014}$), because the empirical research started already in 2014. For comparing the literature and empirical results, the complexity drivers, published in 2015 ($N_{Lit.\ 2015}$), were also considered. For the pretest ($N_{Pretest\ T}$), we used the complexity drivers, which were already mentioned in literature before 2015 and added additional drivers from other fields along the value chain (N_{VC}). Our pretest resulted in 59 complexity drivers, which were considered truly relevant by the pretesters ($N_{rel.}$). Furthermore, the experts mentioned 5 additional important and relevant complexity drivers ($N_{Experts}$). Thus, our final questionnaire comprised 64 complexity drivers in total ($N_{Questionnaire\ T}$). As a result of our empirical research, the respondents regarded 30 different complexity drivers as drivers that have a strong or very strong influence in principle ($N_{eval.}$). Based on these drivers, different main complexity drivers in the different fields of industry are identified (see Table 17). Furthermore, some industries are influenced by more complexity drivers than other industries.

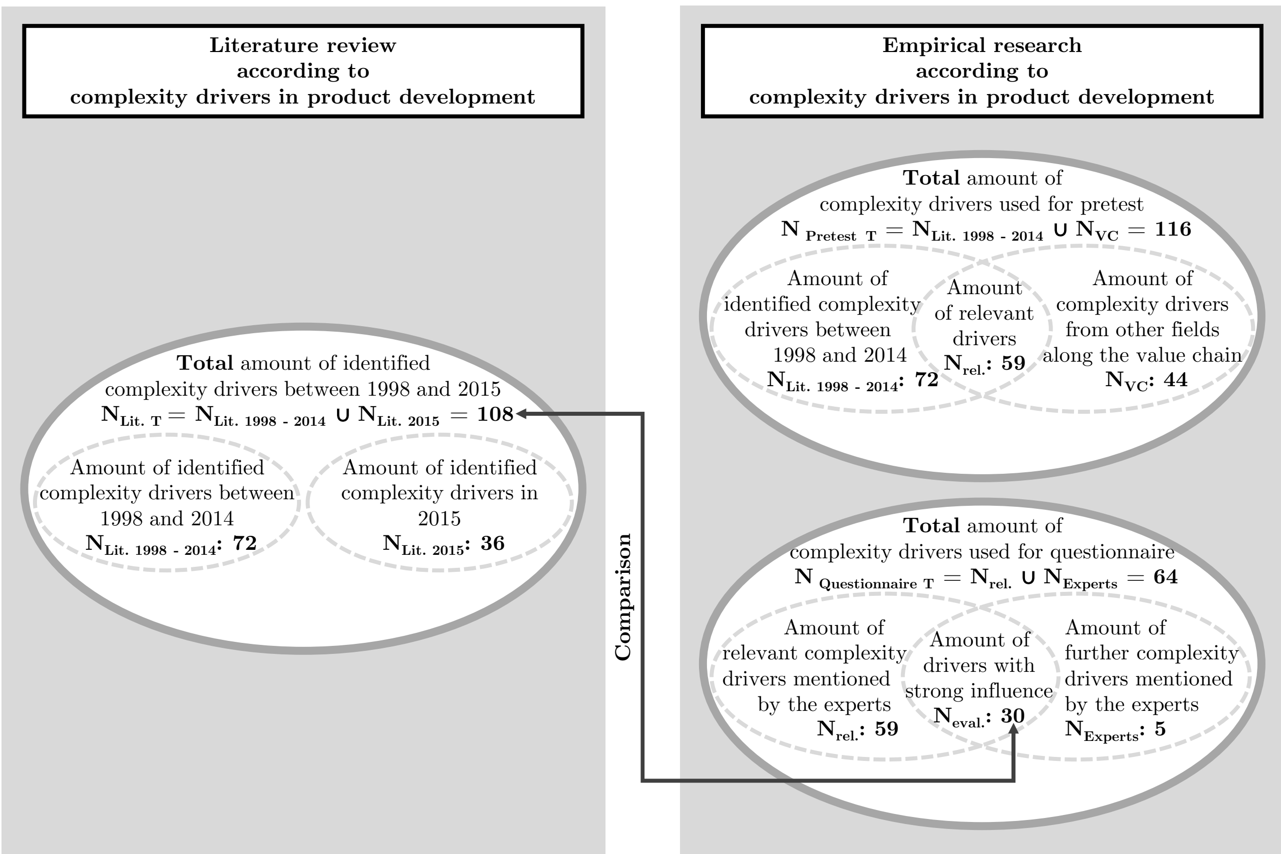


Figure 15: Comparison of literature findings versus empirical findings regarding complexity drivers in product development

In summary, 108 different complexity drivers are described in literature (see Figure 15). In contrast, 30 complexity drivers with a strong or very strong influence on product development were mentioned by experts. These drivers can be separated in 14 external, 9 internal correlated and 7 internal autonomous drivers. Furthermore, 6 main complexity drivers were identified. No further complexity drivers were mentioned in our final empirical research. The different complexity drivers, which were mentioned by the experts are described in Table 17 (see subsection 4.4.2).

In literature, the main complexity drivers are mostly related to internal complexity (see Table 14). Thus, the origin of complexity is seen mainly inside the company itself. In contrast, the identified complexity drivers from the empirical research are mostly related to external complexity. In practice, complexity is regarded as a condition, which is mostly influenced from outside. The reason may be that companies can influence and handle internal complexity actively, thus we come to the conclusion that the companies are aware of it. Contrary to internal complexity, external complexity cannot or nearly cannot be influenced by the company itself and is often unknown. Thus, the respondents consider the complexity phenomenon as an external source and want to receive additional information regarding external complexity drivers to increase their knowledge.

There were some major differences between our research and literature regarding specific complexity drivers, as well as driver categories and their influence on company's complexity. In literature, organizational complexity is described as an important driver for company's complexity (see Table 14, subsection 4.2.2). In our empirical research, we found out that the organization and its complexity does not have a major influence on company's complexity (see Figure 14, subsection 4.4.1). The same could be found regarding the complexity driver categories technological complexity (external and internal), product and product portfolio complexity, as well as product development complexity and their specific drivers (see Table 14, subsection 4.2.2). In literature, these categories and their specific drivers are also described as important sources for company's complexity. However, in our research, the respondents classified these categories and their specific drivers not as important and relevant sources for managing company's complexity (see Table 17, subsection 4.4.2).

From scientific perspective, this comparison allows a concentration on the most important complexity drivers (see Table 17). Furthermore, the differences between literature and practice regarding specific drivers and driver categories are pointed out. From practical perspective, this comparison allows not only an insight about the drivers, known in literature, but also about the drivers that are considered important by other practitioners from other fields of industry. This overview increases transparency for the practitioner.

Further research should analyze the differences between theory and practice more in detail and the empirical findings should be used for further discussions und evaluations in literature. In addition, the companies should compare and evaluate their complexity drivers with those described in literature to question their own identified complexity drivers.

4.5 Conclusion, outlook and limitations

The objective of this empirical research is to develop additional knowledge for science and practice by identifying and analyzing existing complexity drivers in science and practice in the field of product development. Furthermore, the results are compared with the literature findings to identify commonalities and differences and to identify further research gaps.

In the first step before starting our empirical study, we reviewed the literature regarding complexity drivers and their effects (see subsection 4.2.2). Next, we searched for previously existing empirical studies regarding complexity management and gaps in literature (see subsection 4.2.3). Our literature search resulted in 72 empirical studies regarding complexity management. As a result of analyzing all previous empirical studies, only 6 studies are focused on product development. Furthermore, we found out that an empirical research in the field product development in manufacturing companies in Germany, including the identification and analysis of complexity drivers and their effects does not exist yet. In this chapter, we want to close this gap.

For our empirical research, we used the methodology of Flynn *et al.* (1990, pp. 253-255). In the section 4.3, the research methodology, the objectives, the sample description and the methods for statistical analysis are described. For data collection, a standardized questionnaire, consisting of 15 questions and a fixed response possibility, was sent in 2 stages by e-mail to 3,086 companies in 2015 and 2016. Only companies with more than 50 employees and located in Germany were selected. In total, 295 questionnaires were completed. The response rate resulted in 10.5%. Industry's range contained 11 different fields of industry. For this empirical research, we determined 4 empirical research questions, which were answered as follows.

Answering the first empirical research question (**RQ3**), product development's characteristics of the participating companies are analyzed regarding product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; the height of the own value adding percentage, as well as organization's influence on product development's complexity. The results are described in detail in subsection 4.4.1.

For answering the second empirical research question (**RQ4**), the empirical data regarding complexity drivers was analyzed and evaluated. Complexity drivers have an influence on a company's complexity and are the basis for a target-oriented complexity management. Based on the statistical analysis, some industries are influenced by more complexity drivers than other industries. For example, the automotive industry is influenced by 12 complexity drivers. In contrast, the chemical & pharmaceutical industry is influenced by only 6 drivers. Furthermore, some complexity drivers are more important than other drivers, because these drivers occur in most fields of industry. These include the complexity drivers market's economic factors, variety of customer requirements, individuality of customer demands, number and strength of competitors, product range/portfolio and amount of simultaneous projects (see Table 17).

As a further result, complexity in product development is mostly influenced by external complexity drivers. We also found out that different fields of industry are influenced by individual main complexity drivers. For example, the technical industries are characterized by the 6 main complexity drivers market's economic factors, variety of customer requirements, individuality of customer demands, number and strength of competitors, product range/portfolio and amount of simultaneous projects. In contrast, the resource industries are influenced by 5 complexity drivers: Variety of customer requirements, individuality of customer demands, political framework conditions, demand's dynamics, as well as technological progress.

It was surprising that the respondents did not evaluate the complexity driver categories technological complexity (external and internal), product and product portfolio complexity, as well as product development complexity and their specific drivers with a strong or very strong influence on product development's complexity, although product development is characterized by these categories.

To identify the relationships and interdependencies between the different complexity drivers, a correlation analysis was conducted. As a result of this analysis, strong correlations between different complexity drivers occur in the categories society complexity, demand complexity, general market-related complexity, technological complexity (external and internal), supply complexity, target complexity, customer complexity, product and product portfolio complexity, product development complexity, production complexity, process complexity, as well as planning, control and information complexity and organizational complexity. Beyond, very strong correlations occur between the 2 categories process complexity and planning, control and information complexity. Based on the correlation analysis, a factor analysis with varimax rotation was used for complexity driver's aggregation. The factor analysis was performed by the statistic software SPSS 21. As a result of the factor analysis, 7 factors were identified, reflecting the complexity drivers: Company's complexity, product and technology complexity, customer's complexity, market complexity, supply complexity, environmental and society complexity, as well as target complexity.

Next, complexity driver's influences on product development's complexity in the 4 categories time, quality, costs and flexibility were analyzed (see Table 20) to answer the third empirical research question (**RQ5**). As a result of our empirical research, high complexity has mostly a strong or very strong effect on the 4 attributes product development time, adherence to deadlines in product development, product quality and product development's costs in general. Also, high complexity has a strong effect on the development time in nearly all industry branches. Furthermore, high complexity has a stronger effect in technical industries than in others. In the technical industries (e.g. automotive or engineering), the most important attributes are product development time, adherence to deadlines in product development, product quality, product development's direct costs and product development's costs in general. In the resource industries (e.g. petroleum & plastics or glas, ceramic, pit & quarry), high complexity has a strong or very strong effect on the attributes product development time and adherence to deadlines in product development and is thus most important for complexity management. In the consumer goods industries (e.g. food, forage & tobacoo or clothing & textile), only 1 attribute is highly influenced by complexity and important for complexity management: Product development time.

Answering the last empirical research question (**RQ6**), the empirical findings about the complexity drivers are compared with the literature findings to identify the significant differences and commonalities (see subsection 4.4.3). In literature, 108 different complexity drivers are described in total without prioritization by the authors. In contrast, in our empirical study only 30 complexity drivers with a strong or very strong influence on product development are mentioned and prioritized by experts.

Summarizing the results of our empirical research, we developed some additional knowledge regarding complexity management, as well as its drivers and effects in product development for science and practice.

From scientific perspective, we connected scientific research with the real world by conducting a transparent, systematic, explicit and reproducible empirical research. Further, we compared the empirical results with literature to identify commonalities and differences and to close a currently existing gap in scientific literature, since no empirical research regarding complexity drivers and their effects in product development exists yet. In our empirical research, we found out that 30 complexity drivers with a strong or very strong influence on product development and 4 effects of high complexity are mentioned by experts. In literature, 108 different drivers and 18 effects are described without prioritization. Further, the experts stated that complexity in product development is mostly influenced by external complexity drivers. In literature, complexity in product development is mostly influenced by internal drivers. This draws to the conclusion that internal drivers are not considered as problems, because these drivers can be handled by the company itself, whereas external complexity drivers cannot be influenced by the company itself and are therefore regarded more as problems. Thus, the practitioners need more and specific information about these drivers. Regarding organization's influence on product development's complexity, the authors in literature came to the conclusion that organization has a direct influence. In our research, the respondents specified that the organization has no negative influence on product development's complexity. Based on these results, the researcher receives an overview about what is already known in practice and can confirm theoretical findings or can develop new ideas, theories or hypotheses.

From practical perspective, the practitioners receive an overview about complexity perception in product development by other practitioners and from other fields of industry. In our research, we found out that product development's characteristics in the different fields of the German manufacturing industry are characterized by a medium and big product and variant range with a product life cycle length of more than 72 months. In contrast, the length of product development process is less than 25 months. The products predominantly consist of many different components, materials and technologies and the product development process consists of many different processes. Relating to company's own value adding percentage in product development, there was no explicit recognizable tendency. Regarding the complexity drivers in product development, we found out that some industries are influenced by more complexity drivers than other industries. For example, the industries automotive, petroleum & plastics and food, forage & tobacco are influenced by 12 different complexity drivers. In contrast, the electrical & optics industry or the chemical & pharmaceutical industry are influenced by only 6 drivers. Furthermore, the following drivers are identified as important drivers for product development's complexity in most fields of industry: Market's economic factors, variety of customer requirements, individuality of customer demands, number and strength of competitors, product range/portfolio and amount of simultaneous projects. Seperating the results according to the different fields of industry, it can be seen that the different industry clusters are characterized by a specific amount of important complexity drivers: Technical industry (N: 6), resource industry (N: 5) and consumer goods industry (N: 5). Based on a factor analysis, the complexity drivers were aggregated to 7 factors, which reflect the complexity drivers: Company's complexity, product and technology complexity, customer's complexity, market complexity, supply complexity, environmental and society complexity, as well as target complexity. This aggregation helps the practitioners to focus their activities regarding complexity management in product development on these specific complexity sources within the company. Another purpose of this research was to analyze the effects of high complexity on product development to give the practice a specific indication. In our research, we identified 4 different effects in the categories time, quality and costs and over all fields of industry: Product development time, adherence to deadlines in product development, product quality and product development's costs in general. Within the different fields of industry, the results can deviate. This overview increases transparency and helps the practitioner to answer the questions "What complexity drivers have a high influence on product development's complexity and are thus relevant for the company?" and "What effects does high complexity within the company have on product development?".

As already mentioned, further research is needed to analyze and explain the differences between literature and practice. Based on our empirical findings, further discussions and evaluations can be performed in literature. Our research was focused on the manufacturing industry of Germany in 2015 and 2016. Future research may also include other countries and sectors, as well as companies with less than 50 employees. It would be interesting to compare the empirical results from our study with the results from a further study, which is conducted in other fields of industry or countries/regions. Furthermore, the development of complexity drivers and their importance for a company over time would also be interesting. Therefore, the same empirical research should be repeated in the future (e.g. 5 to 10 years) to identify differences and commonalities of complexity driver's perception between now and the future.

5 Single approaches for complexity management in product development: An empirical research

5.1 Introduction

Companies in high-technology marketplaces are confronted with technology innovations, dynamic market environment, market's globalization, increasing number of demanding customers and uncertainty. These are trends that manufacturing companies cannot escape (Voigt *et al.*, 2011, p. 1; Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Perona and Miragliotta, 2004, p. 103). According to ElMaraghy and ElMaraghy (2014, p. 1), "increasing global competition makes it necessary to generate wealth by being more competitive and offering goods and services that are differentiated by design and innovation". For company's success, it is fundamental to design and manufacture new products quickly and bring them to market with customer's individual settings (Lübke, 2007, pp. 2-3, ElMaraghy and ElMaraghy, 2014, p. 1). Customer's individual needs and the increasing global competition are the reasons, why many companies are present in the market with a diversified product portfolio (ElMaraghy and ElMaraghy, 2014, p. 1). In consequence, the companies cope with these trends by developing new product variants, which lead to an increased complexity in the company (Brosch and Krause, 2011, p. 1) and especially in product development (Kim and Wilemon, 2012, p. 1). For developing new product variants, resources are required (Wleklinski, 2001, p. 27, Bohne, 1998, pp. 9-10), which have to be procured (Vogel, 2017, p. 92). In product development, the amount of required resources is associated with the amount of product variants and product development's complexity (Bohne, 1998, pp. 9-10). According to Wleklinksi (2001, p. 27), development project's success is connected with the amount of available resources. Procurement's objective is to provide all required objects for the company, which are not produced by itself (Arnold, 1997, p. 3). Procurement's effort is connected with the amount of required resources (Franke and Firchau, 2001, p. 9). Thus, resources and their procurement become a central role for product development and company's success (Vogel, 2017, pp. 84, 92).

Increasing complexity is one of the biggest challenges that manufacturing companies have to face today (ElMaraghy *et al.*, 2012, p. 793). In addition, increasing complexity is often related to increasing costs (Meyer, 2007, p. 94). Complexity is a phenomenon and evolutionary process, which presents a challenge, especially for science and engineering. Complexity is characterized through change, choice and selection, as well as perception and progress. Furthermore, complexity is intensified through innovations in products and processes (Warnecke, 2010, p. 639). Originally, the term "complexity" comes from the Latin word "complexus", which signifies "extensive, interrelated, confusing, entwined or twisted together" (ElMaraghy *et al.*, 2012, p. 794; Grübner, 2007, pp. 40-41; Gießmann, 2010, p. 30). In literature, many different definitions for the term "complexity" are presented, because the meaning is vague and ambiguous. However, an explicit, universal and widely accepted definition does not exist (Brosch and Krause, 2011, p. 2; ElMaraghy *et al.*, 2012, p. 794).

Product development is an important source to be competitive and to gain a competitive advantage over other business firms (Schaefer, 1999, p. 311). During the product development process, 80% of product costs are defined (Bayer, 2010, p. 89). Furthermore, the corresponding processes for production and procurement are determined (Dehnen, 2004, p. 26; Lübke, 2007, pp. 70-71; Bick and Drexl-Wittbecker, 2008, pp. 70-71). According to Schulte (1992, pp. 86-87), increasing complexity, especially in product development, leads to increasing costs in all parts along the value chain. Over the last years, product development's relevance has changed significantly and became a central importance in a company's strategy (Davila, 2000, p. 383). According to Bick and Drexl-Wittbecker (2008, p. 20) and Davila (2000, p. 386), product development is one of the most complex tasks and uncertain processes in the company. Product development's objective is "to translate an idea into a tangible physical asset" (Davila, 2000, p. 385). Complexity in product development has continuously increased in the last years (Lübke, 2007, pp. 1-4; Krause, Franke and Gausemeier, 2007, pp. 3-4; ElMaraghy *et al.*, 2012, pp. 793-797) and has the biggest influence on a company's complexity (Krause, Franke and Gausemeier, 2007, pp. 3-4, 23). Managing company's complexity is a strategic issue to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). In literature, several objectives and strategies (Wildemann, 2012, p. 69), as well as a vast number of different single approaches for managing complexity are described (Gießmann, 2010, pp. 57-70).

For a target-oriented and effective complexity management, information is needed. In principle, the information needed can be gathered through scientific research, especially literature research, or empirical research. To compare literature results with the real world, empirical studies are conducted. During the last 15 years, several empirical studies regarding complexity management were conducted in various fields of industry and regions/countries and are focused on different fields in the company and along the value chain. Previous empirical studies regarding complexity management in the field product development have been done by 6 different authors. However, none of the previous empirical studies regarding complexity management in product development concerns specific approaches for complexity management in product development. Furthermore, the previous empirical studies do not compare their results with literature. As a result of this, we want to close this research gap by our empirical research to verify scientific findings and to compare the literature and the empirical results to identify commonalities and differences.

This research is structured as follows: In section 5.2, an overview about the research methodology is given and a literature overview about the different single approaches, which are applied for managing company's complexity and their objectives, is presented. Furthermore, the existing empirical researches in the field of complexity management are described and analyzed to identify gaps in literature. Section 5.3 is focused on the empirical research and represents the research methodology and objectives, questionnaire's design, as well as the data collection methodology and sample description. In section 5.4, the empirical findings are described. In the first part, the sample results and the data validation are presented. The second part gives an overview about the results regarding the single approaches for managing complexity and their targeted strategies. In the last part of section 5.4, the empirical findings are compared with the existing literature results to identify commonalities and differences. Section 5.5 concludes the study by answering the research questions. Furthermore, the research gap is closed with implications for future research.

5.2 Literature review

5.2.1 Research methodology and boundary definition

The purpose of this chapter is to compare literature's findings regarding specific single approaches for complexity management with the real world to increase transparency and knowledge by identifying similarities and differences. For data collection, an empirical study in the manufacturing industry of Germany was conducted. In literature, a vast number of different single approaches for managing variety and complexity are described (Gießmann, 2010, p. 56). Single approaches are methods or tools, used for structuring or dealing with a task, situation or problem (Oxford Living Dictionaries, 2017a; Dictionary, 2017; Lindemann and Baumberger, 2006, pp. 7-9; Kieviet, 2014, pp. 2, 44; Krause, Franke and Gausemeier, 2007, p. 9; Wildemann, 1998, p. 55). They are considered as an entity on its own and have no interrelations with other approaches. Further, the approaches are focused on specific objectives and strategies (e.g. complexity reduction or avoidance) to solve a problem in the company and to achieve a long-term or overall aim (Lindemann and Baumberger, 2006, p. 9; Cambridge Dictionary, 2017; Oxford Living Dictionaries, 2017b).

In the first step before starting an empirical research, the existing literature and empirical studies must be reviewed. For the literature review, we used the methodology of Fink (2014, p. 3) and determined the following 3 research questions:

- RQ 1: What different single approaches for complexity management currently exist in scientific literature?
- RQ 2: What focus and objectives do the existing single approaches have?
- RQ 3: What empirical studies in the field of complexity management in general and regarding specific complexity management single approaches currently exist in scientific literature?

In the next step, we defined the right search terms and databases. The search terms are formulated with a particular grammar and logic and are based on the research questions. In our literature research, we searched in English- and German-language literature and databases to extend the amount of relevant literature. The finalized search terms are created through an iterative process, starting with 1 key word and adding more, inclusive all potential synonyms of the particular key words in order to identify all important literature sources. According to Vogel and Lasch (2016, p. 5) and Vogel (2017, p. 95), the literature research was performed in the following 8 English and German databases, which are specialized in science and economics: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink. The time period was restricted between 1900/01/01 and 2015/12/31, because our empirical study was performed in the years 2015 and 2016 and we want to compare the empirical results with the existing literature in the same time period.

The literature search resulted in a certain amount of literature sources, including research papers from journals, conference proceedings, books, essays and PhD theses. The specific amount of literature sources regarding the 2 issues are presented as follows: Single approaches for complexity management (130,722 literature sources) and empirical studies in the field complexity management (26,699 literature sources). However, several literature sources were found multiple times.

To identify the relevant literature sources, the existing literature was analyzed, evaluated and synthesized based on the aforementioned research questions by using qualitative data analysis techniques. According to Fink (2014, p. 5), literature research always accumulates many publications, but only a few are relevant for scientific research. Thus, it is necessary to synthesize the results to identify the relevant literature sources. For the qualitative data analysis, we followed the methodology of Vogel and Lasch (2016, p. 6), which is described in detail in their publication. The results are described in the following subsections 5.2.2 and 5.2.3.

5.2.2 Single approaches for managing complexity

As already mentioned, the researched literature was analyzed and synthesized based on the qualitative content analysis techniques and the aforementioned research questions. The synthesizing process resulted in 288 relevant literature sources in the time period between 1962 and 2015 (see Table 52 and 53 in the appendix).

In literature, a vast number of different single approaches for managing complexity in the company and along the value chain (including the fields product development, procurement, production, logistics, etc.) with specific purposes (e.g. complexity reduction or avoidance) are described. As already mentioned, a single approach is a method, which is focused on a specific strategy and is used for structuring or dealing with a task or situation in a company to solve a problem or to achieve a particular objective.

Generally, the approaches can be divided in 4 overall categories according to their focus: Product, product portfolio, process and organization (Lasch, 2014, pp. 216-228; Gießmann, 2010, pp. 57-70; Gießmann and Lasch, 2011, pp. 11-20). According to literature, the most important approaches in each category are presented and discussed as follows:

Approaches, focused on **product,** can be differentiated in 2 purposes: Product splitting or product bundling. However, the 2 types stand in no competition to each other. The right combination of both can help the company to achieve potentials (Wildemann, 2013, p. 148). Modular concept, modular system, standardization and differential construction are focused on product splitting. The approaches using same parts, platform concept and integral construction are focused on product bundling (Wildemann, 2013, p. 148; Gießmann, 2010, p. 57). The objective of modular concepts is to separate the product in independent and standardized components, modules or assembly units, called subsystems (Göpfert and Steinbrecher, 2001, pp. 353-356; Piller and Waringer, 1999, pp. 37-40). The subsystems can be substituted at any time (Piller and Waringer, 1999, pp. 38-39). Baldwin and Clark (2000, p. 63) define a module as a “unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units”. The modular concept is the basis for other approaches, such as modular system and platform concept (Lindemann and Maurer, 2006, p. 43). A modular system is characterized by 1 or more base plates, on which different mounting parts can be assembled (Rapp, 1999, p. 52). Modular system and the modular concept are similar, but the modular concept has no base plate (Zich, 1996, p. 40). Standardization is used to reduce the variety on the level of product (Jeschke, 1997, p. 22). The objective is to standardize objects (Maune, 2001, pp. 25-26; Bohn, 2009, p. 232). Components that have optical or technological differences, but the same function, can be substituted by identical elements (Wildemann, 2013, pp. 143-146, 155-160). In differential construction, the components are separated in different component parts to increase the amount of same parts (Ehrlenspiel, 1995, p. 419; Schuh and Schwenk, 2001, p. 79). The opposite of differential construction is integral construction. The objective is to combine different parts to 1 component to reduce variety (Ehrlenspiel, 1995, p. 419; Schuh and Schwenk, 2001, p. 80). Further product bundling strategies are the platform concept and using same parts. Using same parts is the overall use of standardized parts in the product (Stang, Hesse and Warnecke, 2002, p. 110). Contrary to the standardization, the concept using same parts reduces functionally different parts or devices to 1 identical part or material basis (Bliss, 2000, p. 42). The objective of a platform concept is to use same parts in different product lines, brands or product life cycles. The platform concept is a special case of the modular concept (Ley and Hofer, 1999, p. 57). It consists of a summary of components, functions and interfaces, which are standardized over the whole product family (Schuh and Schwenk 2001, p. 87, Schuh, 2005, p. 133).

Focused on **product portfolio**, 3 different approaches can be used for managing complexity in the company: Packaging, reducing product range and reducing of customers. Packaging's objective is to reduce the product portfolio complexity by limitation of product's configuration possibilities (Bliss, 2000, p. 40; Schuh and Schwenk, 2001, p. 83). For packaging, a fixed combination of layout properties is built from several functions or modules (Schuh, 1989, p. 59). Another approach for reducing the product portfolio and its complexity is to reduce the product range. Products with high complexity and low benefit are removed from the portfolio (Bliss, 2000, pp. 39-40; Kirchhof, 2003, p. 116). An alternative for reducing the product portfolio is to reduce the number of customers. Certain customers or groups of customers are not supplied in the future (Bliss, 2000, p. 41). In certain situations, the approaches reducing product range and reducing of customers are correlated directly (Gießmann, 2010, p. 64).

In the category **process**, also 3 different approaches exist for complexity management: Postponement concept, standardization of processes and modularity of processes. The postponement concept is based on shifting the order penetration point to the end of the value chain (Klug, 2010, pp. 55-56; Gießmann, 2010, p. 64, Köster, 1998, pp. 82-83). Company's performance process, especially the production process, is separated in 2 parts: Order neutral and order related. Ideally, the order penetration point should be located at the transition point between order neutral and order related processes (Köster, 1998, pp. 82-83). The standardization of processes is an approach for coordinating future situations by providing a concrete solution (Dehnen, 2004, pp. 154-155). It is used in often recurring and less diversifying processes. For reducing process complexity, the inputs and outputs, the work flow, as well as the interfaces are fixed and standardized (Meyer, 2007, p. 63). The process modularity is based on dividing a large process into smaller sub-processes. They can be designed and operated independently, while the sub-processes ensure that the whole process fulfills its objectives (Blecker and Abdelkafi, 2006a, p. 77; Abdelkafi, 2008, pp. 152-154). In literature, further single approaches, such as sourcing strategies, production segmentation or self-monitoring control cycles (kanban systems), exist in the category process. However, these single approaches are out of focus in our empirical research, because we focused our research on approaches for complexity management in the field of product development. According to Wildemann (1998, pp. 60-61), Reiners and Sasse (1999, pp. 230-231), Bliss (2000, pp. 45-54), Klug (2010, pp. 67-68, 117-124), Gießmann and Lasch (2011, pp. 17-20), Reiss (2011, p. 78) and Wildemann (2012, pp. 223-229), these approaches are focused more on logistics, production and procurement than on product development.

The approaches, focused on **organization,** can be subdivided in delayering and empowerment. Delayering is characterized by reducing the levels of hierarchy in the company to increase the work and information flow. Espinosa, Harnden and Walker (2007, pp. 334-335, 340-344) argue that companies with strong hierarchical structures have problems with managing dynamic environmental complexity. Another approach, focused on organization, is empowerment. The objective is to delegate decision-making authority to subordinated hierarchies or operational levels to reduce coordination and organizational complexity (Bliss, 2000, pp. 49-50; Meffert, Burmann and Kirchgeorg, 2012, p. 314; Adam and Rollberg, 1995, pp. 667-669).

As a result of our literature research, the mentioned approaches are applied for 6 different purposes, called complexity strategies: Complexity reduction, mastering, avoidance, outsourcing and increasing, as well as general for complexity management. Complexity reduction is based on a direct and short-term reduction of parts, products and processes (Wildemann, 2013, pp. 76-77). Mastering of complexity is characterized by effectively handling unavoidable complexity along the value chain. It has a medium-term to long-term focus (Wildemann, 2005, p. 36; Wildemann, 2013, pp. 76, 78). The strategy with the longest horizon is complexity avoidance. The objective is to avoid and prevent the generation of complexity early (Wildemann, 2013, pp. 76, 79). The idea of complexity outsourcing is to displace complexity to an external business partner to reduce company's internal complexity, costs and risks (Rosenberg, 2002, p. 192; Schönsleben, 2011, p. 72, Gabath, 2008, p. 67). To complement the complexity strategies, the target-oriented increasing of complexity is also referred to in literature (Meyer, 2007, p. 35; Puhl, 1999, p. 23; Kirchhof, 2003, pp. 62-63). However, the complexity strategies outsourcing and increasing have less relevance in literature and practice (Schoeneberg, 2014a, p. 21; Meyer, 2007, p. 35). Complexity acceptance is also mentioned in literature as a complexity strategy (Hasenpusch, Moos and Schwellbach, 2004, p. 137). However, in this research, complexity acceptance is not considered, because in literature no specific procedure has been pointed out for science and practice.

To identify the main purpose (complexity strategy) of each approach, a literature analysis was performed based on the results of our literature research (see subsection 5.2.1).

Table 21 presents the results of our literature analysis and gives an overview about the different approaches, the total amount of literature sources, which are concerned with the specific single approaches and the main purpose (complexity strategy) of each approach. Since several literature sources assign more than one purpose or strategy for a certain complexity management approach, the total amount of literature occurrence (see Table 21, last column) is higher than the total amount of literature sources (see Table 21, third column). The most often used complexity strategies are color-marked.

For example, 158 authors describe modular concept as a complexity management approach. However, modular concept is assigned for the different complexity strategies 186 times. Modular concept is assigned in literature 121 times for complexity reduction (65%), 36 times (19%) for complexity mastering and 20 times (11%) for complexity avoidance. Furthermore, modular concept is already assigned in literature for general complexity management (N: 9; 5%).

As a result of this literature analysis, all approaches are mostly used for complexity reduction. Thus, this is the main complexity strategy regarding the single complexity approaches. An overview about the authors, the existing single approaches for complexity management in literature and the particular purposes is cited in the appendix (see Table 52 and Table 53). Another result of our literature analysis is that literature focuses more and more on the different complexity management single approaches over time. Generally, the literature sources are published between the time period 1962 and 2015. However, the amount of publications regarding all single approaches has increased between 2005 and 2015. Thus, there is an increasing interest in science regarding the specific complexity management approaches over the last 10 years. For example, 110 publications (70%) concerning modular concept were published between 2005 and 2015. For the other approaches, the trends are analogously (see Table 52 and Table 53 in the appendix).

Table 21: Overview about applied complexity management approaches, their purposes and literature occurrence

Focus	Single approaches for complexity management	Total amount of literature sources, which concern with a specific approach	Targeted complexity strategy (Purpose)						Total amount of literature occur-rences
			Reduction	Mastering	Avoidance	Increasing	Outsourcing	General	
			N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
Product	Modular concept	158	**121 (65%)**	36 (19%)	20 (11%)	0 (0%)	0 (0%)	9 (5%)	186 (100%)
	Modular system	60	**38 (57%)**	16 (24%)	7 (10%)	0 (0%)	0 (0%)	6 (9%)	67 (100%)
	Standardization	90	**72 (73%)**	9 (9%)	12 (12%)	0 (0%)	0 (0%)	6 (6%)	99 (100%)
	Using same parts	56	**38 (64%)**	10 (17%)	8 (14%)	0 (0%)	0 (0%)	3 (5%)	59 (100%)
	Platform concept	87	**68 (72%)**	16 (17%)	6 (6%)	0 (0%)	0 (0%)	5 (5%)	95 (100%)
	Differential construction	19	**12 (50%)**	2 (8%)	1 (4%)	6 (25%)	2 (8%)	1 (4%)	24 (100%)
	Integral construction	29	**19 (58%)**	5 (15%)	3 (9%)	4 (12%)	0 (0%)	2 (6%)	33 (100%)
Product portfolio	Packaging	23	**19 (83%)**	2 (9%)	0 (0%)	0 (0%)	0 (0%)	2 (9%)	23 (100%)
	Reducing product range	25	**22 (85%)**	0 (0%)	1 (4%)	0 (0%)	0 (0%)	3 (12%)	26 (100%)
	Reducing of customers	11	**10 (91%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (9%)	11 (100%)
Process	Postponement concept	40	**26 (60%)**	11 (26%)	2 (5%)	0 (0%)	0 (0%)	4 (9%)	43 (100%)
	Standardization of processes	20	**13 (57%)**	1 (4%)	7 (30%)	0 (0%)	0 (0%)	2 (9%)	23 (100%)
	Modularity of processes	15	**12 (60%)**	2 (10%)	5 (25%)	0 (0%)	0 (0%)	1 (5%)	20 (100%)
Organization	Delayering	9	**5 (56%)**	3 (33%)	0 (0%)	0 (0%)	0 (0%)	1 (11%)	9 (100%)
	Empowerment	14	**9 (64%)**	2 (14%)	0 (0%)	0 (0%)	0 (0%)	3 (21%)	14 (100%)

■ Complexity strategy, which is mostly used in literature for a specific complexity management single approach (more than 50%)

5.2.3 Existing empirical studies in the field of complexity management and identification of gaps in literature

Before starting an empirical research, it is important to review existing studies in the same or a similar scientific area to get an overview about their objectives, research methodologies and findings (Madu, 1998, pp. 354-355). According to Madu (1998), we performed a literature research to identify all existing empirical researches in the field of complexity management in manufacturing companies and especially regarding complexity management single approaches during the last years. The literature research was performed analogously to the literature research about the approaches for complexity management (see subsection 5.2.1).

As a result of our literature research, we found 72 different empirical studies in the field complexity management in the time period between 1999 and 2015. The identified studies were analyzed and synthesized according to their content, research objectives, focus, field of industry, region/country, research period and applied data collection methodology. The empirical studies are focused on 8 different fields: General in manufacturing companies (N: 32; 44%), product development (N: 6; 8%), production (N: 3; 4%), logistics (N: 5; 7%), order processing/distribution/sale (N: 4; 6%), internal supply chain (N: 16; 22%), remanufacturing (N: 2; 3%) and other fields (N: 4; 6%).

Previous empirical studies regarding product development have been done by 6 authors with different objectives between the time period 2005 and 2013: Li *et al.* (2005), Kim and Wilemon (2009; 2012), Newman (2009), Chronéer and Bergquist (2012) and Grussenmeyer and Blecker (2013). The empirical studies were conducted in different countries and fields of industry and the authors pursued different objectives as well.

As a result of the analysis of the existing empirical studies regarding complexity in product development, as well as other fields (e.g. general in manufacturing companies, production, logistics, etc.), we come to the conclusion that an empirical research regarding specific single approaches for managing complexity in product development and their main objectives does not exist yet. In this chapter, we want to close the referred literature gap by presenting an empirical research in the field of product development in manufacturing companies in Germany.

5.3 Empirical research

5.3.1 Research methodology and objectives

For our empirical research, we followed the methodology of Flynn *et al.* (1990, pp. 253-255) based on social sciences. Flynn *et al.* (1990, pp. 253-255) describe a 6-stage systematic approach for conducting an empirical research, starting with the determination of the theoretical foundation (see Figure 16). This helps the researcher to describe, what happens in the real world (Moody, 2002, p. 1). In stage II, the research design, which is applied to the research problem and the theoretical foundation, is selected (e.g. survey, single or multiple case study, etc.). Next, the data collection methods (e.g. questionnaire, interviews, historical archive analysis, etc.) and sample description for research's implementation (e.g. sample industry and size, country, pilot testing, etc.) are selected in the stages III and IV. Several data collection methods are described in literature. In principle, the existing methods can be used alone or can be combined for better results. However, the mostly used data collection method is the questionnaire (Flynn *et al.*, 1990, pp. 258-259). Before preparing the research report for publication (stage VI), the collected data is processed and analyzed in stage V (Flynn *et al.*, 1990, pp. 264-268).

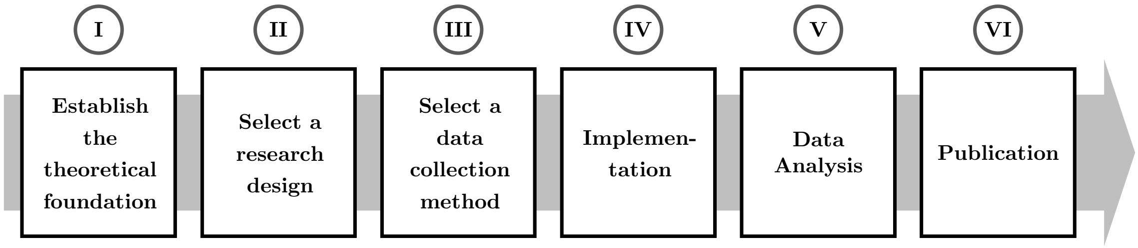


Figure 16: Six stage systematic approach for empirical research, developed by Flynn *et al.*

To perform an empirical research, the research questions and objectives must be defined. In this case, we use an empirical research to document the current state in practice regarding the application of specific single approaches for complexity handling in the manufacturing industry of Germany. Furthermore, we compare the results from literature with the results from the real world to identify commonalities and differences. For our research, we determined 2 further research questions, focused on our empiricism (called empirical research questions) to close the research gap:

- RQ 4: What single approaches are applied for complexity management in product development and what specific complexity strategy are they focused on?
- RQ 5: What are the significant differences and commonalities between literature and the practical (empirical) results?

5.3.2 Questionnaire's design, data collection methodology, sample description and statistical analysis

The implementation of a research starts with selection of the data collection method and the sample description (Flynn *et al.*, 1990, pp. 256-263). In our research, we applied a standardized questionnaire with 4 questions and a fixed response possibility for data collection method. The data was collected from a stratified random sample out of a given population of 17,862 manufacturing companies, located in Germany with more than 50 employees. The population of 17,862 manufacturing companies was determined based on the Amadeus database, where all manufacturing companies of Germany are documented at the beginning of our empirical research in 2015. According to Gießmann (2010, p. 89), only companies with more than 50 employees were selected, because it is supposed that the complexity phenomenon primarily occurs in bigger companies rather than in smaller. The research was conducted in 2015 and 2016. A standardized questionnaire was sent in 2 stages by e-mail to 3,086 companies, exclusive of service and printing companies. In the cover letter, the companies were asked to send the questionnaire to an experienced employee from the product development department. The stratified random sample size (n = 1,565) is calculated based on the population (N = 17,862), a safety factor (t = 2), which depends on respondents' level of significance, the proportion of the elements within the random sample, which fulfills the feature characteristic (p = 0.5) and the sampling error (d = 0.05) (Mayer, 2013, p. 66; Raab, Poost and Eichhorn, 2009, p. 84). According to questionnaire's design, we structured the questionnaire in 2 main parts and started with general information regarding the respondents: Company size, field of industry and respondent's position in the company. The second part concerns questions regarding the application of specific single approaches for complexity management in product development. The questions were formulated based on the research questions. The scale items were designed as statements and the interviewees were asked about their assessment. In our questionnaire, we used nominal scales and ordinal scales for measurement. Before starting our empirical research, the questionnaire was pretested in 2014 by 40 experts from the potential target group to check and refine the wording, understanding, relevance, as well as the measurement instrument, the questionnaire length and the time for questionnaire's responding. Based on the results and comments from the experts, the questionnaire was revised and checked again by a smaller group of experts.

A questionnaire belongs to the quantitative research methods and must be analyzed by using statistical methods to validate an existing theory (Flynn *et al.*, 1990, pp. 264-267). For statistical analysis, several statistical tests or data analysis techniques exist that a researcher can use. However, there is no general rule to select a particular approach (Madu, 1998, p. 354). In our empirical research, we analyzed the empirical findings by using the descriptive data analysis techniques means, frequencies and proportions. Further, some multivariate analysis techniques were applied as well. However, the results were not significant. Thus, these results are not described in detail in this chapter.

5.4 Analysis of empirical research and findings

5.4.1 Sample results and data validation

As already mentioned, the questionnaire was sent by e-mail to 3,086 manufacturing companies with more than 50 employees, located in Germany. For response rate's counting, the researcher has to determine the net sample size by reducing the total sample size based on the amount of e-mails that were undeliverable or rejected by the companies (Gießmann, 2010, p. 90). The final sample size was a total of 2,817 companies. In this research, 295 questionnaires were answered completely and resulted in a response rate of 10.5%. According to Meffert (1992, p. 202), this response rate is acceptable. Industry's range contained 11 different fields of industry, which were clustered in the following 4 industry clusters according to their characteristics: Technical industry, resource industry, consumer goods industry and others. About 60% of the respondents were from the technical industry, such as engineering (30.5%), metal (10.5%), electrical & optics (9.8%), automotive (8.1%) (see Figure 17). Traditionally, the technical industry is Germany's major field of industry with a percentage of 63.5% based on the Amadeus database. For result's validation, the percentage of the empirical research was compared with the percentage of the database to identify commonalities and differences. In all industry clusters, the percentage of empirical research and database are very close. Thus, distortions can be avoided and the empirical findings are representative for generalization.

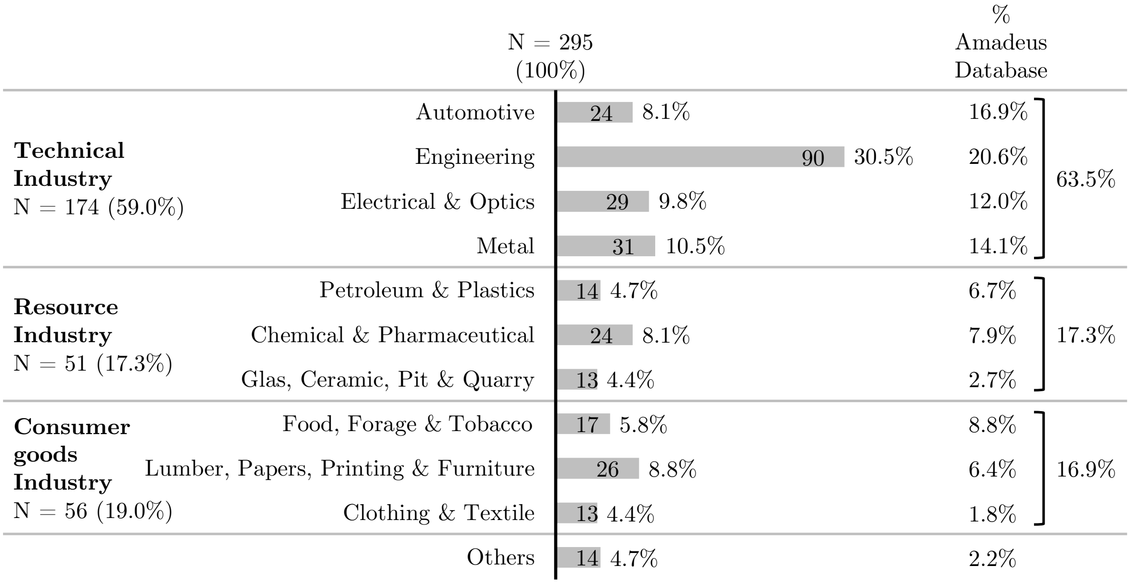


Figure 17: Frequency of received questionnaires according to industry and comparison of results and database's percentage

Next, the number of employees and the position profile of the respondents were analyzed (see Figure 18 and 19). The small and middle-sized companies between 50 and 250 employees are the biggest group in our empirical research with 61.8% (see Figure 18). Larger companies with more than 250 employees represent 38.2%. These results show that small and middle-sized companies are highly interested in empirical studies regarding complexity management and especially in product development.

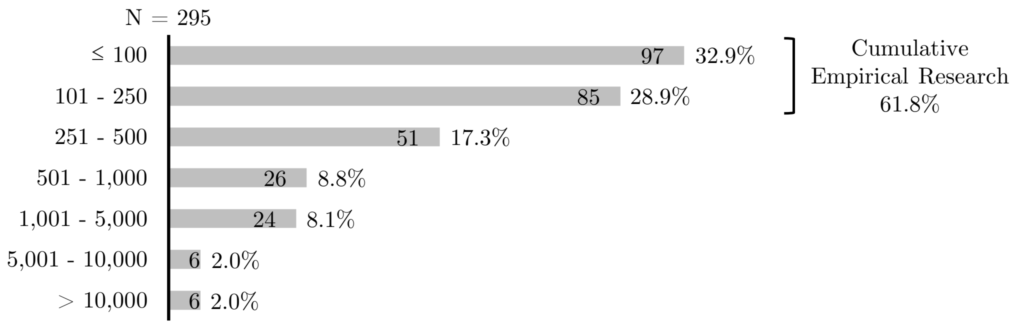


Figure 18: Overview about the number of employees of the respondents

The analysis of the respondent's position profile shows that complexity in product development is an important issue for management (see Figure 19). In total, 80% of the respondents can be allocated to the upper management, consisting of the following 3 groups: Presidents, CEOs and COOs (18.0%), directors and division managers (26.1%) as well as senior managers and department managers (35.9%).

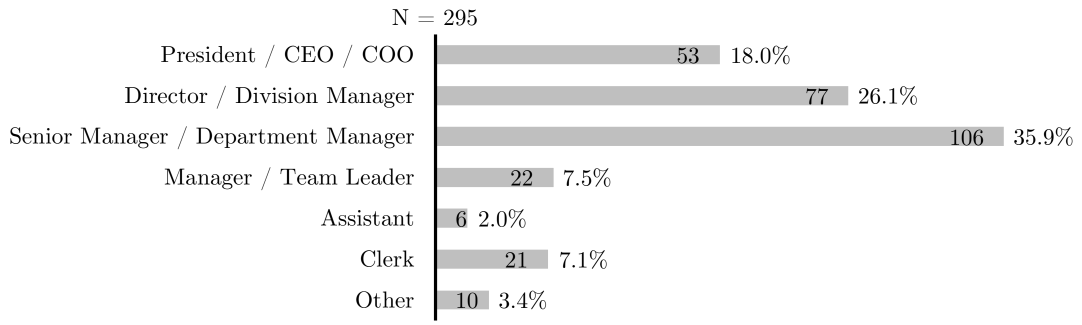


Figure 19: Overview about the position profile of the respondents

5.4.2 Results regarding single approaches for managing complexity

The main research objective was to identify the approaches, which were applied for complexity management in product development and the specific strategy, they are focused on. In literature, 15 approaches were applied, focused on 6 different complexity strategies (see subsection 5.2.2). The 6 complexity strategies comprise 5 specific strategies (reduction, mastering, avoidance, increasing and outsourcing), as well as a more superior strategy (general for complexity management). In our empirical research, we used only the 5 specific strategies in our questionnaire to reduce the amount of response possibilities and get a precise answer from the respondents. The approaches were evaluated by the respondents according to their awareness level, application in the company and focused strategy. The questionnaire responses were analyzed by descriptive statistics. Based on the statistical analysis, the results were clustered in 3 groups:

- Single approaches, which are known and applied,
- Single approaches, which are known and not applied,
- Single approaches, which are unknown.

We assumed that a specific approach that is not known cannot be applied by the company. Figure 20 presents the principle, which is applied for analyzing the empirical results according to approach's knowledge and application in the different branches.

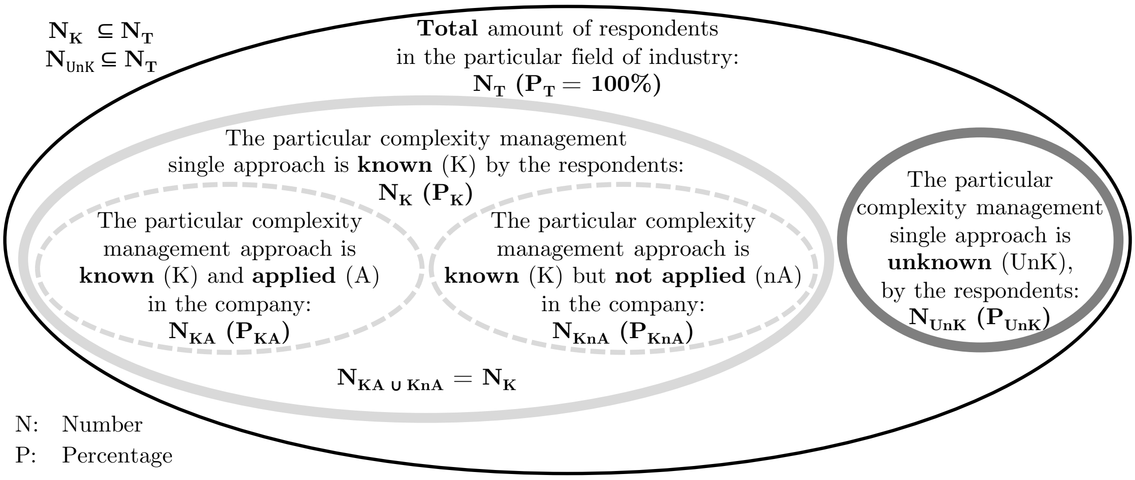


Figure 20: Analysis principle according to single approach's knowledge and application

Based on Figure 20, the empirical data is structured and analyzed. The analytical results are shown in Table 22. In Table 22, the different single approaches and respondent's answers according to approach's knowledge and application are presented. Furthermore, the empirical results are separated based on respondent's field of industry. For example, in the automotive industry, the approach modular concept is known by 23 respondents (N_K) and unknown by only 1 (N_{UnK}). Even though, 23 respondents know the approach modular concept, only 17 (N_{KA}) apply this approach for complexity management in their company. In addition, 6 respondents know this approach, but do not apply it (N_{KnA}). The reason for this should by analyzed in further research.

The approaches, which are predominantly known and used for complexity management in the company, were color-marked. For our color marking, we defined 3 different levels according to the Normal distribution and the standard deviation σ, in which results could be found from the average: 100% - 95% (±3σ), 94% - 68% (±2σ) and less than 68% (±σ) (Hellwig and Sypli, 2014, p. 42).

Table 22: Empirical results according to approach's knowledge and application (Part A)

Explanation:

- 100% - 95% (black)
- 94% - 68% (grey)
- less than 68% (white)

N_K (P_K) Known
N_{UnK} (P_{UnK}) Unknown
N_{KA} (P_{KA}) Known & Applied
N_{KnA} (P_{KnA}) Known & not Applied

		Technical Industry				Resource Industry			Consumer goods Industry				
		Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	**Others**	**Weighted Average**
Single approaches	**N_T:**	**24**	**90**	**29**	**31**	**14**	**24**	**13**	**17**	**26**	**13**	**14**	**Ø**
Modular concept	N_K	23	86	28	26	10	18	11	13	25	11	13	
	P_K	**96%**	**96%**	**97%**	**84%**	**71%**	**75%**	**85%**	**76%**	**96%**	**85%**	**93%**	89%
	N_{UnK}	1	4	1	5	4	6	2	4	1	2	1	
	P_{UnK}	4%	4%	3%	16%	29%	25%	15%	24%	4%	15%	7%	11%
	N_{KA}	17	80	23	14	6	15	9	11	20	8	11	
	P_{KA}	**74%**	**93%**	**82%**	54%	60%	**83%**	**82%**	**85%**	**80%**	**73%**	**85%**	81%
	N_{KnA}	6	6	5	12	4	3	2	2	5	3	2	
	P_{KnA}	26%	7%	18%	46%	40%	17%	18%	15%	20%	27%	15%	19%
Modular system	N_K	23	86	26	26	10	19	12	12	25	11	13	
	P_K	**96%**	**96%**	**90%**	**84%**	**71%**	**79%**	**92%**	**71%**	**96%**	**85%**	**93%**	89%
	N_{UnK}	1	4	3	5	4	5	1	5	1	2	1	
	P_{UnK}	4%	4%	10%	16%	29%	21%	8%	29%	4%	15%	7%	11%
	N_{KA}	17	76	22	16	8	17	8	10	17	9	9	
	P_{KA}	**74%**	**88%**	**85%**	62%	**80%**	**89%**	67%	**83%**	**68%**	**82%**	**69%**	79%
	N_{KnA}	6	10	4	10	2	2	4	2	8	2	4	
	P_{KnA}	26%	12%	15%	38%	20%	11%	33%	17%	32%	18%	31%	21%
Standardization	N_K	23	85	26	28	11	20	13	16	25	12	14	
	P_K	**96%**	**94%**	**90%**	**90%**	**79%**	**83%**	**100%**	**94%**	**96%**	**92%**	**100%**	93%
	N_{UnK}	1	5	3	3	3	4	0	1	1	1	0	
	P_{UnK}	4%	6%	10%	10%	21%	17%	0%	6%	4%	8%	0%	7%
	N_{KA}	21	80	23	25	11	20	12	16	23	10	11	
	P_{KA}	**91%**	**94%**	**88%**	**89%**	**100%**	**100%**	**92%**	**100%**	**92%**	**83%**	**79%**	92%
	N_{KnA}	2	5	3	3	0	0	1	0	2	2	3	
	P_{KnA}	9%	6%	12%	11%	0%	0%	8%	0%	8%	17%	21%	8%
Using same parts	N_K	23	86	26	28	10	18	12	15	24	12	14	
	P_K	**96%**	**96%**	**90%**	**90%**	**71%**	**75%**	**92%**	**88%**	**92%**	**92%**	**100%**	91%
	N_{UnK}	1	4	3	3	4	6	1	2	2	1	0	
	P_{UnK}	4%	4%	10%	10%	29%	25%	8%	12%	8%	8%	0%	9%
	N_{KA}	22	82	24	22	9	17	10	13	19	12	11	
	P_{KA}	**96%**	**95%**	**92%**	**79%**	**90%**	**94%**	**83%**	**87%**	**79%**	**100%**	**79%**	90%
	N_{KnA}	1	4	2	6	1	1	2	2	5	0	3	
	P_{KnA}	4%	5%	8%	21%	10%	6%	17%	13%	21%	0%	21%	10%
Platform concept	N_K	23	76	26	26	11	16	10	12	25	10	12	
	P_K	**96%**	**84%**	**90%**	**84%**	**79%**	67%	**77%**	**71%**	**96%**	**77%**	**86%**	84%
	N_{UnK}	1	14	3	5	3	8	3	5	1	3	2	
	P_{UnK}	4%	16%	10%	16%	21%	33%	23%	29%	4%	23%	14%	16%
	N_{KA}	14	54	20	14	10	14	6	8	18	8	7	
	P_{KA}	61%	**71%**	**77%**	54%	**91%**	**88%**	60%	67%	**72%**	**80%**	58%	70%
	N_{KnA}	9	22	6	12	1	2	4	4	7	2	5	
	P_{KnA}	39%	29%	23%	46%	9%	12%	40%	33%	28%	20%	42%	30%
Differential construction	N_K	14	56	14	15	6	10	4	8	15	7	9	
	P_K	58%	62%	48%	48%	43%	42%	31%	47%	58%	54%	64%	54%
	N_{UnK}	10	34	15	16	8	14	9	9	11	6	5	
	P_{UnK}	42%	38%	52%	52%	57%	58%	**69%**	53%	42%	46%	36%	46%
	N_{KA}	8	39	8	9	2	3	1	6	6	4	4	
	P_{KA}	57%	**70%**	57%	60%	33%	30%	25%	**75%**	40%	57%	44%	57%
	N_{KnA}	6	17	6	6	4	7	3	2	9	3	5	
	P_{KnA}	43%	30%	43%	40%	67%	**70%**	**75%**	25%	60%	43%	56%	43%

Table 22: Empirical results according to approach's knowledge and application (Part B)

Explanation:

- 100% - 95% (black)
- 94% - 68% (grey)
- less than 68% (white)

N_K (P_K) Known
N_{UnK} (P_{UnK}) Unknown
N_{KA} (P_{KA}) Known & Applied
N_{KnA} (P_{KnA}) Known & not Applied

		Technical Industry				**Resource Industry**			**Consumer goods Industry**				
		Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	**Others**	**Weighted Average**
Single approaches	N_T:	**24**	**90**	**29**	**31**	**14**	**24**	**13**	**17**	**26**	**13**	**14**	**Ø**
Integral construction	N_K	16	63	18	24	8	13	7	8	22	7	12	
	P_K	67%	70%	62%	**77%**	57%	54%	54%	47%	**85%**	54%	**86%**	67%
	N_{UnK}	8	27	11	7	6	11	6	9	4	6	2	
	P_{UnK}	33%	30%	38%	23%	43%	46%	46%	53%	15%	46%	14%	33%
	N_{KA}	12	49	14	16	3	8	4	4	15	4	6	
	P_{KA}	**75%**	**78%**	**78%**	67%	38%	62%	57%	50%	**68%**	57%	50%	68%
	N_{KnA}	4	14	4	8	5	5	3	4	7	3	6	
	P_{KnA}	25%	22%	22%	33%	63%	38%	43%	50%	32%	43%	50%	32%
Packaging	N_K	21	61	19	17	9	13	9	9	17	7	10	
	P_K	**88%**	**68%**	66%	55%	64%	54%	**69%**	53%	65%	54%	**71%**	65%
	N_{UnK}	3	29	10	14	5	11	4	8	9	6	4	
	P_{UnK}	12%	32%	34%	45%	36%	46%	31%	47%	35%	46%	29%	35%
	N_{KA}	11	41	10	7	4	8	5	6	10	5	6	
	P_{KA}	52%	67%	53%	41%	44%	62%	56%	67%	59%	**71%**	60%	59%
	N_{KnA}	10	20	9	10	5	5	4	3	7	2	4	
	P_{KnA}	48%	33%	47%	59%	56%	38%	44%	33%	41%	29%	40%	41%
Reducing product range	N_K	23	81	26	26	11	20	13	15	25	10	13	
	P_K	**96%**	**90%**	**90%**	**84%**	**79%**	**83%**	**100%**	**88%**	**96%**	**77%**	**93%**	89%
	N_{UnK}	1	9	3	5	3	4	0	2	1	3	1	
	P_{UnK}	4%	10%	10%	16%	21%	17%	0%	12%	4%	23%	7%	11%
	N_{KA}	14	47	15	18	8	17	11	11	17	9	10	
	P_{KA}	61%	58%	58%	**69%**	**73%**	**85%**	**85%**	**73%**	**68%**	**90%**	**77%**	67%
	N_{KnA}	9	34	11	8	3	3	2	4	8	1	3	
	P_{KnA}	39%	42%	42%	31%	27%	15%	15%	27%	32%	10%	23%	33%
Reducing of customers	N_K	20	59	22	21	9	16	11	15	18	10	13	
	P_K	**83%**	66%	**76%**	**68%**	64%	67%	**85%**	**88%**	**69%**	**77%**	**93%**	73%
	N_{UnK}	4	31	7	10	5	8	2	2	8	3	1	
	P_{UnK}	17%	34%	24%	32%	36%	33%	15%	12%	33%	23%	7%	27%
	N_{KA}	6	20	3	12	0	11	5	7	8	3	6	
	P_{KA}	30%	34%	14%	57%	0%	**69%**	45%	47%	44%	30%	46%	38%
	N_{KnA}	14	39	19	9	9	5	6	8	10	7	7	
	P_{KnA}	70%	66%	86%	43%	**100%**	31%	55%	53%	56%	70%	54%	62%
Postponement concept	N_K	14	46	15	9	5	9	5	5	15	5	8	
	P_K	58%	51%	52%	29%	36%	38%	38%	29%	58%	38%	57%	46%
	N_{UnK}	10	44	14	22	9	15	8	12	11	8	6	
	P_{UnK}	42%	49%	48%	**71%**	64%	62%	62%	**71%**	42%	62%	43%	54%
	N_{KA}	5	26	9	4	4	6	2	3	7	2	1	
	P_{KA}	36%	57%	60%	44%	**80%**	67%	40%	60%	47%	40%	13%	51%
	N_{KnA}	9	20	6	5	1	3	3	2	8	3	7	
	P_{KnA}	64%	43%	40%	56%	20%	33%	60%	40%	53%	60%	**88%**	49%
Standardization of processes	N_K	23	85	27	28	11	23	12	15	26	11	14	
	P_K	**96%**	**94%**	**93%**	**90%**	**79%**	**96%**	**92%**	**88%**	**100%**	**85%**	**100%**	93%
	N_{UnK}	1	5	2	3	3	1	1	2	0	2	0	
	P_{UnK}	4%	6%	7%	10%	21%	4%	8%	12%	0%	15%	0%	7%
	N_{KA}	21	74	25	26	8	22	12	15	21	11	12	
	P_{KA}	**91%**	**87%**	**93%**	**93%**	**73%**	**96%**	**100%**	**100%**	**81%**	**100%**	**86%**	90%
	N_{KnA}	2	11	2	2	3	1	0	0	5	0	2	
	P_{KnA}	9%	13%	7%	7%	27%	4%	0%	0%	19%	0%	14%	10%

Table 22: Empirical results according to approach's knowledge and application (Part C)

Explanation:

- 100% - 95%
- 94% - 68%
- less than 68%

N_K (P_K) Known
N_{UnK} (P_{UnK}) Unknown
N_{KA} (P_{KA}) Known & Applied
N_{KnA} (P_{KnA}) Known & not Applied

		Technical Industry				Resource Industry			Consumer goods Industry				
		Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	**Others**	**Weighted Average**
Single approaches	**N_T:**	**24**	**90**	**29**	**31**	**14**	**24**	**13**	**17**	**26**	**13**	**14**	**∅**
Modularity of processes	N_K	21	68	22	26	9	14	11	12	22	7	11	
	P_K	**88%**	**76%**	**76%**	**84%**	64%	58%	**85%**	**71%**	**85%**	54%	**79%**	76%
	N_{UnK}	3	22	7	5	5	10	2	5	4	6	3	
	P_{UnK}	12%	24%	24%	16%	36%	42%	15%	29%	15%	46%	21%	24%
	N_{KA}	17	46	15	19	6	14	7	8	13	5	8	
	P_{KA}	**81%**	**68%**	**68%**	**73%**	67%	**100%**	64%	67%	59%	**71%**	**73%**	71%
	N_{KnA}	4	22	7	7	3	0	4	4	9	2	3	
	P_{KnA}	19%	32%	32%	27%	33%	0%	36%	33%	41%	29%	27%	29%
Delayering	N_K	23	74	25	24	12	19	12	14	24	9	14	
	P_K	**96%**	**82%**	**86%**	**77%**	**86%**	**79%**	**92%**	**82%**	**92%**	**69%**	**100%**	85%
	N_{UnK}	1	16	9	7	2	5	1	3	2	4	0	
	P_{UnK}	4%	18%	14%	23%	14%	21%	8%	18%	85	31%	0%	15%
	N_{KA}	14	47	14	12	8	13	6	6	11	6	8	
	P_{KA}	61%	64%	56%	50%	67%	**68%**	50%	43%	46%	67%	57%	58%
	N_{KnA}	9	27	11	12	4	6	6	8	13	3	6	
	P_{KnA}	39%	36%	44%	50%	33%	32%	50%	57%	54%	33%	43%	42%
Empowerment	N_K	22	70	26	27	12	17	9	13	21	11	14	
	P_K	**92%**	**78%**	**90%**	**87%**	**86%**	**71%**	**69%**	**76%**	**81%**	**85%**	**100%**	82%
	N_{UnK}	2	20	3	4	2	7	4	4	5	2	0	
	P_{UnK}	8%	22%	10%	13%	14%	29%	31%	24%	19%	15%	0%	18%
	N_{KA}	14	52	21	14	10	13	8	8	14	5	9	
	P_{KA}	64%	**74%**	**81%**	**70%**	**83%**	**76%**	**89%**	62%	67%	45%	64%	72%
	N_{KnA}	8	18	5	8	2	4	1	5	7	6	5	
	P_{KnA}	36%	26%	19%	30%	17%	24%	11%	38%	33%	55%	36%	29%

Table 22 shows that 9 single approaches are predominantly known and applied by more than 68% of the respondents for complexity management in product development: Modular concept, modular system, standardization, using same parts, platform concept, reducing product range, standardization of processes, modularity of processes and empowerment.

Further analysis of the results of Table 22 shows that other approaches, such as differential or integral construction, packaging, reducing of customers or postponement concept are not commonly known and applied in product development by the respondents. Furthermore, even though the approach delayering is commonly known in practice, it is not commonly applied in product development. These results draw to the conclusion that the application of specific approaches, such as packaging, reducing of customers, postponement concept or delayering are not used for complexity management in product development by the respondents, because the application of these approaches cannot be influenced by the product development department itself. Reasons for this could be that these approaches originate in other fields along the value chain, such as production or distribution and sale. Another surprising result is that the approaches differential or integral construction are not commonly known and applied for complexity management in product development, although these approaches can be assigned to product development. According to literature, integral and differential construction are used for product design during the product development process (Ehrlenspiel, 1995, pp. 414-422; Schuh and Schwenk, 2001, pp. 71-80). Therefore, it would be interesting to investigate the reasons for this discrepancy.

Comparing the results within the 3 industry clusters technical industry, resource industry and consumer goods industry regarding the 9 single approaches that are predominantly known and applied by more than 68% of the respondents, it can be seen that some fields of industry apply specific approaches more often than others. Within the technical industry, the field engineering is the benchmark for modular concept, modular system, as well as standardization. The approaches using same parts and modularity of processes are applied most often by the automotive industry. Further, the approaches platform concept and empowerment are mainly applied in the electrical and optics industry and the approach reducing product range is mainly applied in the metal industry. The approach standardization of processes is applied in the same way in 2 fields of industry: Electrical and optics, as well as metal. Furthermore, our analysis shows that for most approaches, the percental value for "approach is known and applied (P_{KA})" of the different fields of industry within the technical industry cluster does not vary much. For example, the percental values within the approach standardization vary from 94% (engineering industry) to 89% (metal industry). However, there are some approaches with a great variation between the highest and lowest percental value (e.g. modular concept: 93% - engineering industry vs. 54% - metal industry). Another surprising result is that the automotive industry has the second lowest value within the approach platform concept. In literature, platform concept is often described as an important strategy for complexity management and product development in the automotive industry. The objective is to reduce complexity by increasing the use of same parts (see subsection 5.2.2). Furthermore, platform concept has a direct influence on product development's strategy and costs, as well as on logistics and production (Maune, 2001, pp. 29-30; Adam, 1998, p. 60). Further research should analyze the reasons for this result. Regarding the resource industry cluster, the chemical and pharmaceutical industry is the leading industry for the approaches modular concept, modular system, standardization, using same parts, reducing product range and modularity of processes. The approach standardization is applied by the petroleum and plastics industry in the same way as by the chemical and pharmaceutical industry. The platform concept is also most often applied by the petroleum and plastics industry. Furthermore, the approaches standardization of processes and empowerment are mainly known and applied by the glas, ceramic, pit and quarry industry. Within the consumer goods industry cluster, the industry branches food, forage and tobacco, as well as clothing and textile are the leading branches. The approaches modular concept, modular system, standardization, as well as standardization of processes are mainly known and applied by the food, forage and tobacco industry. The approach standardization of processes is applied by the clothing and textile industry in the same way. Further, the approaches using same parts, platform concept, reducing product range and modularity of processes are applied most in the clothing and textile industry. In addition, the field of industry lumber, papers, printing and furniture is the leading industry regarding the approach empowerment. Analyzing the different percental values for "approach is known and applied (P_{KA})" of the different fields of industry within the resource and the consumer goods industry analogously, we identified approaches with a low variation (e.g. resource industry: standardization: 100% vs. 92% or consumer goods industry: standardization: 96% vs. 92%), as well as with a high variation (e.g. resource industry: platform concept: 91% vs. 60% or consumer goods industry: reducing product range: 90% vs. 73%).

Based on the analytical results, which are presented in Table 22, the different single approaches were analyzed in the next step according to their targeted strategy. For data analysis, only the approaches and strategies that are known and applied by the respondents were used. In our research, several respondents assign more than one purpose or strategy to a certain complexity management approach. As already mentioned, the same occurs in literature (see subsection 5.2.2).

Table 23 presents an overview about the applied approaches and their purposes for complexity management in product development. The complexity strategies with the highest values are color-marked. For example, in our research, 133 respondents use the approach modular concept for complexity mastering (43.3%) and 96 respondents use it for complexity reduction (31.3%). The strategy with the highest value has priority 1 (black color-marked) and the strategy with the second highest value has priority 2 (grey color-marked). However, no explicit tendency towards a specific strategy could be identified in this case and for most other approaches. Only the approach "modularity of processes" is assigned with more than 50% to the strategy complexity mastering. Based on the results, the complexity approaches are mainly used for complexity reduction or mastering. However, as already mentioned, no explicit tendency towards 1 specific strategy can be identified. The strategy complexity avoidance is also used in practice, but is not as important as complexity reduction or mastering. The strategies, which are used fewest in the manufacturing industry, are complexity increasing and outsourcing.

Table 23: Empirical results according to applied single approaches and their purpose

Complexity strategy with: ■ Priority 1 and the highest value ■ Priority 2 and the second highest value		**Complexity strategy**									
		Reduction		**Mastering**		**Avoidance**		**Increasing**		**Outsourcing**	
Focus	**Single approaches**	N	%	N	%	N	%	N	%	N	%
Product	Modular concept	**96**	**31.3%**	**133**	**43.3%**	47	15.3%	18	5.9%	13	4.2%
	Modular system	**99**	**30.8%**	**123**	**38.3%**	64	19.9%	22	6.9%	13	4.0%
	Standardization	**127**	**37.5%**	**100**	**29.5%**	**100**	**29.5%**	6	1.8%	6	1.8%
	Using same parts	**108**	**34.2%**	**100**	**31.6%**	91	28.8%	13	4.1%	4	1.3%
	Platform concept	**91**	**34.6%**	**84**	**31.9%**	69	26.2%	14	5.3%	5	1.9%
	Differential construction	**30**	**23.1%**	**53**	**40.8%**	17	13.1%	18	13.8%	12	9.2%
	Integral construction	**47**	**27.3%**	**69**	**40.1%**	30	17.4%	19	11.0%	7	4.1%
Product portfolio	Packaging	**41**	**24.6%**	**65**	**38.9%**	35	21.0%	17	10.2%	9	5.4%
	Reducing product range	**116**	**46.2%**	53	21.1%	**65**	**25.9%**	6	2.4%	11	4.4%
	Reducing of customers	**66**	**46.5%**	28	19.7%	**37**	**26.1%**	6	4.2%	5	3.5%
Process	Postponement concept	**28**	**24.6%**	**48**	**42.1%**	21	18.4%	10	8.8%	7	6.1%
	Standardization of processes	**92**	**29.6%**	**133**	**42.8%**	69	22.2%	8	2.6%	9	2.9%
	Modularity of processes	**54**	**24.5%**	**110**	**50.1%**	35	15.8%	14	6.4%	7	3.2%
Organization	Delayering	52	28.6%	**64**	**35.2%**	**55**	**30.2%**	8	4.4%	3	1.6%
	Empowerment	**62**	**29.5%**	**81**	**38.6%**	48	22.9%	12	5.7%	7	3.3%

After analyzing the different single approaches according to their targeted strategy, the results from Table 23 are separated regarding the different fields of industry and industry clusters. Only the complexity strategies with the highest values in each approach and field of industry are described in Table 24, whereas the strategies with the second, third, etc. highest value are not presented in the table.

For example, in the automotive industry, 38% of the respondents use the approach modular concept for complexity mastering (M). This is the highest value and is therefore presented in Table 24. Furthermore, 28% of the respondents also use this approach for complexity reduction (R), 24% use it for the strategy complexity avoidance (A) and 10% for complexity outsourcing (O). These values are not presented in Table 24. However, there is no explicit tendency in this case, because no complexity strategy is assigned by more than 50% of the respondents. Analyzing the other results, there is often also no explicit tendency towards a specific strategy for most approaches and within the different fields of industry and industry clusters. The complexity strategies, which are assigned by 50%, or more than 50% of the respondents are color-marked.

In Table 23 and 24, it can be seen that the approaches modular concept, modular system, differential and integral construction, packaging, postponement concept, standardization and modularity of processes, as well as delayering and empowerment are applied for complexity mastering in most fields of industry. However, some fields of industry apply these approaches also for complexity reduction, avoidance or increasing, but not for outsourcing. For example, the approach modular concept is applied for complexity mastering by most fields of industry, but also for complexity reduction and avoidance in the industry branches petroleum and plastics; glas, ceramic, pit and quarry, as well as food, forage and tobacco. The single approaches, which are applied for complexity reduction in most fields of industry (e.g. standardization, using same parts, platform concept, etc.) are also used for mastering, avoidance and outsourcing, but not for increasing.

Comparing the percental values within the different industry clusters, it can be seen that only in the technical industry cluster, the combination between the specific single approach and its targeted strategy is often equal. Within the other industry clusters, the results are mostly not consistent regarding the combination between approach and targeted strategy.

Furthermore, within the different fields of industry, several single approaches with different targeted complexity strategies are applied for complexity management in product development. No industrial branch focuses only on 1 specific complexity strategy (see Table 24, last 5 rows). For example, in the automotive industry, 6 approaches are used for complexity reduction (standardization, platform concept, reducing product range, reducing of customers, standardization of processes, empowerment) and 7 for complexity mastering (modular concept, modular system, integral construction, packaging, postponement concept, standardization of processes, modularity of processes). Furthermore, 2 approaches are used for complexity avoidance (using same parts, delayering) and 1 for a targeted complexity increasing (differential construction). Comparing these results overall between the different industry branches, the strategies complexity mastering (N: 7) and complexity reduction (N: 4) are mostly used in the different fields of industry for complexity management.

Table 24: Empirical results according to applied single approaches and their purpose in the different fields of industry

Explanation to complexity strategy with priority 1 and the highest value:

R Reduction
M Mastering
A Avoidance
I Increasing
O Outsourcing

Note: If there is more than one strategy listed, the percentage of the different strategies is equal.

Focus	Single approaches	Technical Industry				Resource Industry			Consumer goods Industry			
		Automotive	Engineering	Electrical & Optics	Metal	Petroleum & Plastics	Chemical & Pharmaceutical	Glas, Ceramic, Pit & Quarry	Food, Forage & Tobacco	Lumber, Papers, Printing & Furniture	Clothing & Textile	**Others**
Product	Modular concept	M 38%	M 48%	M 41%	**M 55%**	R, M 38%	M 41%	R, A 31%	R 40%	M 49%	**M 56%**	A 40%
	Modular system	M 31%	M 44%	M 39%	M 42%	A 33%	R 39%	R 31%	M 47%	M 41%	**R 50%**	R, A 36%
	Standardization	R 35%	R 40%	R 37%	R 35%	A 43%	R 39%	**A 50%**	M 39%	R 41%	R 43%	R 42%
	Using same parts	A 39%	R 36%	R 35%	M 39%	M, A 36%	A 35%	R 40%	M 47%	M 37%	**R 50%**	**A 55%**
	Platform concept	R 39%	R 38%	M 34%	R 44%	**M 50%**	R 35%	R, A 38%	**R 55%**	M 42%	R 44%	**A 63%**
	Differential construction	I 29%	**M 53%**	**M 60%**	M 31%	**A 50%**	R,M, A 33%	**A 100%**	R 33%	R, A 25%	R, M 40%	**M 67%**
	Integral construction	M 31%	M 44%	**M 50%**	R 32%	M, A 33%	R, M 44%	**A 50%**	R, A 40%	M 47%	R,A,I 33%	**M 57%**
Product portfolio	Packaging	M 40%	M 41%	M 40%	M 45%	A 44%	M 45%	R, M 38%	M 44%	M 29%	M, A 40%	R, M 33%
	Reducing product range	R 42%	R 45%	R 41%	A 32%	R 40%	**R 56%**	R 44%	**R 57%**	**R 52%**	R 44%	**R 90%**
	Reducing of customers	**R 55%**	R 38%	R 41%	**R 58%**	R, A 33%	R 38%	R, M, A, O 25%	**R 54%**	**R 62%**	**R 67%**	**R 50%**
Process	Postponement concept	M 36%	**M 50%**	M 47%	M 33%	**R,M 50%**	A, I 33%	**M 50%**	**A 60%**	M 44%	**R 75%**	**A 67%**
	Standardization of processes	R, M 36%	M 45%	M 47%	R, M 32%	**M 54%**	M 38%	**M 50%**	**M 53%**	M 41%	M 42%	R 45%
	Modularity of processes	M 42%	**M 51%**	**M 55%**	M 45%	**M 67%**	R, M 41%	**M 50%**	**M 70%**	**M 57%**	M 38%	R, M 38%
Organization	Delayering	A 43%	M 46%	R,M, A 31%	A 35%	**M 56%**	M, A 32%	A 43%	A 43%	**M 50%**	**R 60%**	R 44%
	Empowerment	R 31%	**M 53%**	M 42%	M 33%	M 44%	R, M 33%	R 42%	M 38%	M 41%	**R 57%**	A 42%
Total amount of applied complexity strategies in each field of industry	**Reduction**	**6**	**5**	**5**	**5**	**4**	**9**	**8**	**6**	**4**	**11**	**8**
	Mastering	**7**	**10**	**11**	**9**	**9**	**8**	**5**	**7**	**11**	**5**	**4**
	Avoidance	**2**		**1**	**2**	**7**	**4**	**7**	**3**	**1**	**2**	**6**
	Increasing	**1**					**1**				**1**	
	Outsourcing							**1**				

5.4.3 Comparison between literature and empirical results

A further research objective was to compare the empirical findings regarding specific complexity management single approaches and their focused strategy with the literature findings to identify commonalities and differences. The comparison gives the opportunity to refine existing scientific knowledge or theories and to identify further research gaps. Table 25 presents a comparison between literature findings and empirical findings regarding the different complexity management single approaches and their targeted strategy. Literature's findings are described in subsection 5.2.2 (see Table 21) and empirical findings are described in subsection 5.4.2 (see Table 23).

Table 25: Comparison of literature findings versus empirical findings

Complexity strategy with:
■ Priority 1 and the highest value
▒ Priority 2 and the second highest value

		Literature findings					**Empirical findings**				
		Complexity strategy					**Complexity strategy**				
Focus	**Single approaches**	**Reduction**	**Mastering**	**Avoidance**	**Increasing**	**Outsourcing**	**Reduction**	**Mastering**	**Avoidance**	**Increasing**	**Outsourcing**
Product	Modular concept	■ •					▒	■ •			
	Modular system	■ •					▒	■ •			
	Standardization	■ •					■ •	▒	▒		
	Using same parts	■ •					■ •	▒			
	Platform concept	■ •					■ •	▒			
	Differential construction	■ •					▒	■ •			
	Integral construction	■ •					▒	■ •			
Product portfolio	Packaging	■ •					▒	■ •			
	Reducing product range	■ •					■ •		▒		
	Reducing of customers	■ •					■ •		▒		
Process	Postponement concept	■ •					▒	■ •			
	Standardization of processes	■ •					▒	■ •			
	Modularity of processes	■ •					▒	■ •			
Organization	Delayering	■ •						■ •	▒		
	Empowerment	■ •					▒	■ •			

In literature, the different complexity approaches are focused on 1 specific strategy with an explicit tendency with more than 50%. All approaches are mostly used for complexity reduction and have priority 1 with the highest value (black color-marked). However, in our empirical research, we found out that the different single approaches could not be assigned to a specific strategy, because no explicit tendency with more than 50% could be identified (see subsection 5.4.2 and Table 23). The complexity strategy, which is assigned mostly by the respondents, has the highest value and priority 1 (black color-marked). Approach's strategy with the second highest value has priority 2 (grey color-marked). As a result of our empirical research, the complexity management approaches are mainly used for complexity mastering and/or reduction. Analyzing the empirical data regarding the specific single approaches within the different fields of industry and industry clusters, the results are similar. No explicit tendency can be identified. Analyzing the empirical data regarding the most applied complexity strategies in the different industry branches, no branch focuses only on 1 specific strategy. However, complexity mastering and complexity reduction are the strategies that are mostly applied.

The reason for this is that the specific approaches are evaluated by the respondents based on different situations and perceptions. Furthermore, in the company, complexity cannot be handled with only 1 specific complexity strategy. For example, companies often cannot reduce complexity to a minimum level, because they need a certain amount of complexity to achieve an optimum complexity degree, to be competitive. Thus, companies are often focused on mastering complexity rather than reducing it. Each new situation or complexity problem requires an individual evaluation with the selection of a specific approach and strategy.

From scientific perspective, this comparison establishes a connection between scientific research and practice and allows the researcher an insight in the real world. This study gives the researcher an overview about, what is already known in practice about this issue and practice's tendencies. It closes a currently existing gap in scientific literature by comparing literature findings and empirical findings to identify similarities and differences. Based on this comparison, the theoretical findings in literature can be confirmed, advanced or progressed. Furthermore, the empirical research shows that in practice the application of a specific complexity management single approach depends on the situation and complexity problem, as well as the desired strategy. Thus, the approaches cannot be assigned to 1 specific strategy. Based on this research and comparison, researchers can build new ideas, theories and hypotheses for their own research.

From practical perspective, this empirical study gives the practitioner an overview about the different approaches for complexity management and their focus and targeted strategy. Further, this study also answers the following manager's questions: "What different approaches are used by other practitioners in other fields of industry?" and "What focus or strategy is pursued by other practitioners in other fields of industry by using a specific single approach?" by providing an overview about the complexity management single approaches and their main focus or strategy. However, a specific recommendation regarding the application of a specific single approach cannot be given, because the selection and application of a specific approach and strategy depends on company's situation or complexity problem. However, this empirical research helps the practitioners to find the right approach for their specific situation or complexity problem.

5.5 Conclusion and outlook

This chapter's objective is to provide an overview about the practical application of specific single approaches for complexity management in the manufacturing industry of Germany. Furthermore, the empirical results are compared with the literature findings to identify commonalities and differences for verifying proposed scientific knowledge and theories, as well as to develop additional knowledge for science and practice.

Before starting our empirical study, we reviewed the literature regarding the specific complexity management single approaches and previously existing empirical studies in the field of complexity management (see subsection 5.2.2 and 5.2.3). Furthermore, we reviewed the existing studies, especially regarding specific single approaches for managing complexity in the company and pointed out the gaps in literature.

As a result of our literature search, we identified 72 empirical studies regarding complexity management. However, only 6 studies are focused on product development. As a result of the analysis of the previous empirical studies regarding product development, as well as other fields, we found out that an empirical research in the field product development in manufacturing companies in Germany and focused on the application of specific single approaches for managing complexity in the company and especially in product development does not exist yet. In this research, we want to close this gap.

To conduct this research, we used the methodology of Flynn *et al.* (1990, pp. 253-255). The research methodology, the objectives, the sample description and the methods for statistical analysis are described in the third section (5.3). For data collection, a standardized questionnaire with 4 questions and a fixed response possibility was sent in 2 stages by e-mail to 3,086 companies with more than 50 employees located in Germany. In this research, 295 questionnaires were completed, which resulted in a response rate of 10.5%. Industry's range contained 11 different fields of industry. For statistical analysis, we used the methods from the descriptive statistics. The results are described in section 5.4. For this empirical research, we determined 2 empirical research questions, which were answered as follows.

Answering the first empirical research question (**RQ4**), the data regarding the complexity management approaches, their objectives and practical application was analyzed and evaluated. For complexity management, 15 different approaches focused on 5 different strategies were applied in practice. Table 22 and Table 23 present an overview about the different approaches, their awareness level and application, as well as the focused strategy. As a result, the following 9 approaches are predominantly known and used for complexity management in the manufacturing industry of Germany: Modular concept, modular system, standardization, using same parts, platform concept, reducing product range, standardization of processes, modularity of processes and empowerment. Based on respondent's answers, the approaches differential or integral construction, packaging, reducing of customers or postponement concept are not commonly known and applied in product development. Next, the results of Table 23 are compared within the 3 industry clusters. As a result of this comparison, some industry branches apply specific approaches more often than other branches. Furthermore, the complexity management single approaches are mainly used for complexity reduction or mastering. However, no explicit tendency towards 1 specific strategy can be identified. Analyzing these results regarding the different fields of industry and industry clusters, the results are equal.

Answering the second empirical research question (**RQ5**), the empirical findings regarding the approaches for complexity management were compared with the literature findings to identify the significant differences and commonalities (see subsection 5.4.3). In literature, the approaches are focused mostly on complexity reduction. In our research, we come to the conclusion that the approaches can not be assigned to a specific complexity strategy. Regarding complexity strategy, no explicit tendency can be identified.

Further research should analyze the differences between theory and practice more in detail and the empirical findings should be used for further discussions und evaluations in literature. Furthermore, our research was focused on the manufacturing industry of Germany. Future research may also include other countries and sectors. It would be interesting to compare the empirical results from this study with the results from a further study, which is conducted in other fields of industry or countries/regions.

6 Approach for complexity management in variant-rich product development

6.1 Introduction

Developing and producing individual and complex products for diversified marketplaces at minimum cost is the challenge of the 21st century. Within the last decades, complexity in the company has increased continuously in many industries (Schuh, Arnoscht and Rudolf, 2010, p. 1928; Lübke, 2007, pp. 2-4; Krause, Franke and Gausemeier, 2007, pp. 3-4; ElMaraghy *et al.*, 2012, p. 797). Companies in high-technology marketplaces are confronted with technology innovations, dynamic environmental conditions, changing customer requirements, market's globalization and uncertainty. These are trends that manufacturing companies cannot escape (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 382; Gerschberger *et al.*, 2012, p. 1016). In today's highly competitive environment, it is fundamental for a company's success to bring new products to the market quickly and with customized settings (Augusto Cauchick Miguel, 2007, p. 617; Lübke, 2007, pp. 2-3). As a reaction, the companies are present in the market with a diversified product portfolio (Haumann *et al.*, 2012, p. 107; ElMaraghy and ElMaraghy, 2014, pp. 1-2). Product development is one of the most complex and nontransparent tasks and uncertain processes in the company (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386; Specht and Beckmann, 1996, pp. 25-26). Product development process is confronted with several complexity factors, such as demand variety, uncertain objectives, environmental dynamics, highly time pressure and restricted resources (Wildemann, 2012, p. 202). Dehnen (2004, pp. 33-35) argues that complexity in product development comes generally from a variety of internal and external sources, called complexity drivers. Complexity drivers describe system's complexity and help to evaluate and handle it. Complexity management is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383).

The purpose of this research is to present a praxis-oriented approach for managing complexity in variant-rich product development. The approach was developed based on literature and encourages the reader to manage product development's complexity. Section 6.2 gives a literature overview about complexity management, its properties, requirements and objectives. Furthermore, an overview of existing complexity management approaches in different fields is presented. As a result of the existing complexity management approaches, a new approach for complexity management in variant-rich product development is described in section 6.3 and is applied on a recent development project in the automotive industry. Section 6.4 and 6.5 conclude the chapter and close the research gap with implications for future research.

6.2 Literature review

6.2.1 Complexity management

The origin of the term complexity comes from the Latin word “complexus”, which means “entwined, twisted together” (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). Based on systems theory, complexity is characterized by the amount and diversity of system’s elements, the amount and type of dependencies and the variation of the elements and their dependencies over time (Kersten, 2011, p. 15). Thus, complex systems are characterized by the variety of their states (Schuh, 2005, pp. 34-35).

Generally in literature, increasing complexity is related to increasing costs (Meyer, 2007, p. 94). For example, modifications in product design or process are responsible for product or process variety and generate additional costs. Furthermore, such modifications may have unpredictable effects on the whole development process (Aggeri and Segrestin, 2007, p. 38).

Managing system’s complexity requires an optimum fit between internal and external complexity. Managing complexity comprises designing the necessary variety, handling variety-increasing factors, reducing variety and controlling complex systems (Schuh, 2005, pp. 34-35). Generally, complexity management has several objectives. In literature, the main objectives are reducing, mastering and avoiding complexity (Wildemann, 2012, p. 69; Lasch and Gießmann, 2009a, p. 198; Schuh and Schwenk, 2001, pp. 32-40; Kaiser, 1995, p. 102). Wildemann (2012, p. 69) defines these objectives as the 3 main strategies for complexity management. In addition to the 3 complexity strategies, Krause, Franke and Gausemeier (2007, pp. 15-16) argue that complexity identification, complexity evaluation and the determination of the optimum complexity degree are also important objectives for complexity management and to improve transparency.

Complexity management requires approaches for understanding, simplification, transformation and evaluation of complexity (Hünerberg and Mann, 2009, p. 3). A successful complexity management approach enables a balance between external market’s complexity and internal company’s complexity (Rosemann, 1998, p. 61; Kaiser, 1995, p. 17). Therefore, it is necessary to implement a complexity management in company’s management process as an integrated concept (Kersten, 2011, pp. 17-18).

Product development is mainly characterized by 3 categories: Product, product portfolio and product development process. Based on these categories, the complexity drivers product complexity, product portfolio complexity and process complexity are derived. Complexity drivers are factors or indicators, which influence a system’s complexity (Puhl, 1999, p. 31; Perona and Miragliotta, 2004, p. 104). Thus, managing complexity in product development requires a detailed complexity analysis in these categories (Dehnen, 2004, p. 9). Beyond the mentioned categories, Ponn and Lindemann (2008, p. 7) argue that the applied methods and instruments in product development are also important aspects.

Product complexity is characterized by product’s design, the number of elements or materials and their interdependencies, as well as the dynamics of product’s activity. Product’s activity consists of the rate, at which new products are introduced or existing products are changed (Edersheim and Wilson, 1992, pp. 27-33;

Kirchhof, 2003, p. 40). Product portfolio complexity is determined by the product range or the variant range, the number of their elements and the dynamics of product portfolio's variability (Kirchhof, 2003, p. 40; Lübke, 2007, p. 173; Schoeller, 2009, p. 50). Process complexity is mainly characterized by process design, process dynamics and multidimensional target expectation. Process design contains the number of direct and indirect process steps, their interdependencies, the design of process interfaces, the level of difficulty, as well as the controllability and consistency of each step. Process dynamics refer to the rate, at which processes or product designs and operational parameters are changing. Operational parameters could be tolerances (Edersheim and Wilson, 1992, pp. 28-34; Klabunde, 2003, p. 8; Kirchhof, 2003, p. 40). Furthermore, process complexity describes the multidimensional demand for a structural coordination between different interfaces (Dehnen, 2004, p. 34).

According to complexity management's objectives and product development's characteristics, the requirements for a complexity management approach in variant-rich product development must be defined. In literature, several requirements for a complexity management approach exist. According to Lasch and Gießmann (2009a, pp. 203-206), we defined 11 main requirements and assigned them to the following 3 main categories:

- Structural: Recurring cycle, modular structure.
- Functional: Practicability and transparency, identifying the complexity problem, methods for complexity management, application of key figures, approach for capability planning.
- Cause related: Identifying complexity drivers, identifying complexity driver's interdependencies, evaluation of complexity drivers and evaluation of complexity (degree).

6.2.2 Research methodology and results

This chapter's purpose is to develop a praxis-oriented approach for managing complexity in variant-rich product development. Before developing a new approach, existing literature must be identified, analyzed and evaluated. For this literature review, we determined 2 research questions:

- RQ 1: What different approaches currently exist in scientific literature?
- RQ 2: What structure and focuses do the existing approaches have?

The first step in conducting a literature research is to define the right search terms based on the research questions. In literature, the terms "approach", "model", "method", "concept", "procedure" and "framework" are often used synonymously for describing a complexity management approach. Thus, all terms were used for this literature research. Furthermore, to extend the results and to prevent the elimination of important articles, the research was performed in English and German by using the following 6 databases, specialized in science and economics: Emerald, ScienceDirect, IEEE Xplore, Google Scholar, GENIOS/WISO and SpringerLink. No restrictions were made regarding the research period. The researched literature sources were synthesized based on the aforementioned research questions. This resulted in 47 relevant approaches in the time period between 1992 and 2014 (see Table 26). As a result, 57% of the existing approaches are focused on general in manufacturing companies. The remaining 43% are separated in other fields, such as product development (6.1%), procurement (2.0%), production (10.2%), logistics (4.1%), internal supply chain (16.3%) and distribution (4.1%). Only 3 approaches are focused on product development. In the next step, the identified approaches were analyzed and described according to their structure and targets (see Table 26). Furthermore, the existing approaches were evaluated based on the described requirements to identify deficits (see Table 27). The evaluation is based on the following 3 criteria:

- Fulfilled (+ +): Content and precise methods are described
- Partial fulfilled (+): Content is described without precise methods
- Not fulfilled (-): Content and methods are not described

In the first step, the structure and the targets of all identified approaches were analyzed to identify commonalities and differences. Based on this analysis, 7 stages of complexity management can be identified and are applied in literature (see Table 26): Complexity analysis (N: 36; 77%), complexity evaluation (N: 19; 40%), determination of complexity strategies (N: 38; 81%), determination of appropriate complexity instruments (N: 10; 21%), complexity planning (N: 6; 13%), complexity management's implementation (N: 9; 19%) and complexity controlling (N: 11; 23%). The most applied stages are determination of complexity strategies, complexity analysis and evaluation. Thus, these stages are very important. However, there is no approach, which consists of all stages.

Complexity management in product development is determined by product complexity, process complexity and product portfolio complexity, so we analyzed the literature regarding these categories. Most of the existing approaches have no explicit target or focus. Only 1 approach exists with a focus on all mentioned complexity categories.

In the next step, the identified approaches are evaluated based on the defined 11 main requirements (see subsection 6.2.1). As a result, there is no approach, which fulfills all requirements in total or partially (see Table 27). The evaluation criteria practicability (N: 31; 66%), transparency (N: 40; 85%) and methods for complexity management (N: 31; 66%) are the most fulfilled or partially fulfilled requirements. Thus, the existing approaches are mostly focused on these criteria. They can be defined as the approach's objectives.

In summary, an approach, which consists of all stages and categories and fulfills all requirements in total or partially, does not exist yet. With our complexity management approach, we cover this research gap.

Table 26: Overview about existing complexity management approaches – Evaluation according to approach's structure and target (Part A)

Explanation for focus:

G	General in manufacturing companies
PD	Product development
PC	Procurement
PR	Production
L	Logistics
SC	Internal supply chain
D	Distribution

Explanation for target:

+ +	fulfilled
+	partially fulfilled
-	not fulfilled

		Approach's structure							Target		
Author(s)	**Focus**	Complexity analysis	Complexity evaluation	Determine complexity strategy	Determine complexity instruments	Complexity planning	Implement complexity management	Complexity controlling	Product complexity	Process complexity	Product portfolio complexity
Grossmann (1992, pp. 209-213)	G	•			•		•		-	-	-
Wildemann (1995, pp. 23-24)	PR			•	•				-	-	-
Fricker (1996, pp. 112-114)	G	•	•						-	-	-
Warnecke and Puhl (1997, pp. 360-362)	G	•	•	•					-	+	-
Bliss (1998, pp. 151-164)	G			•					+ +	-	-
Bohne (1998, pp. 91-92)	G	•	•	•				•	-	-	-
Rosemann (1998, pp. 60-62)	G			•					-	-	-
Puhl (1999, pp. 45-97)	G	•				•		•	-	+	-
Wildemann (1999a, pp. 66-67)	PC			•					-	-	-
Bliss (2000, pp. 194-208)	G			•					+ +	-	-
Westphal (2000, p. 28)	L			•					-	-	-
Miragliotta, Perona and Portioli-Staudacher (2002, pp. 382-383, 388-392)	G	•	•	•	•				-	-	-
Kim and Wilemon (2003, pp. 24-27)	PD		•	•			•		-	-	-
Kirchhof (2003, pp. 167-243)	G	•				•			-	-	-
Dehnen (2004, pp. 49-61)	PD			•					+ +	+ +	+ +
Hanenkamp (2004, pp. 59-138)	PR			•		•	•	•	+	+	-
Meier and Hanenkamp (2004, pp. 118-127)	SC	•		•	•				-	-	-
Perona and Miragliotta (2004, pp. 112-114)	PR, L	•		•					-	-	-
Blecker, Kersten and Meyer (2005, pp. 51-52)	G	•	•						-	-	-
Geimer (2005, pp. 45-46)	SC	•		•			•		-	-	-
Geimer and Schulze (2005, p. 102)	SC	•		•			•	•	-	-	-
Anderson *et al.* (2006, p. 21)	G	•	•	•					-	-	-
Greitemeyer and Ulrich (2006, p. 8)	G	•		•		•		•	+	+	-
Denk (2007, pp. 20-21)	G	•		•					-	-	-

Table 26: Overview about existing complexity management approaches – Evaluation according to approach's structure and target (Part B)

Explanation for focus:
G General in manufacturing companies
PD Product development
PC Procurement
PR Production
L Logistics
SC Internal supply chain
D Distribution

Explanation for target:
+ + fulfilled
+ partially fulfilled
- not fulfilled

		Approach's structure							**Target**		
Author(s)	**Focus**	Complexity analysis	Complexity evaluation	Determine complexity strategy	Determine complexity instruments	Complexity planning	Implement complexity management	Complexity controlling	Product complexity	Process complexity	Product portfolio complexity
Marti (2007, pp. 152-153)	G		•	•					+ +	-	-
Meyer (2007, pp. 129-142)	D	•		•				•	-	-	-
Bick and Drexl-Wittbecker (2008, pp. 78-81)	G			•					+ +	+ +	-
Schuh *et al.* (2008, pp. 447-448)	G	•							+ +	-	-
Denk and Pfneissl (2009, pp. 28-32)	G	•		•					-	-	-
Lasch and Gießmann (2009b, pp. 114-118)	G	•	•	•		•	•	•	+	+	+
Lindemann, Maurer and Braun (2009, pp. 61-66)	PD	•		•					+	-	-
Blockus (2010, pp. 269-293)	G	•		•		•		•	-	-	-
Warnecke (2010, p. 641)	G	•	•	•					-	-	-
Isik (2011, pp. 422-423)	SC	•	•	•				•	-	-	-
Kersten (2011, pp. 15-18)	SC	•	•	•					-	-	-
Schawel and Billing (2011, pp. 110-111)	G	•		•					-	-	-
Fabig and Haasper (2012, pp. 17-19)	G	•		•	•		•		+	-	+
Koch (2012, p. 54)	G	•	•	•					-	-	-
Lammers (2012, pp. 85-135)	D	•	•		•				-	-	-
Aelker, Bauernhansl and Ehm (2013, pp. 81-82)	SC	•	•	•					-	-	-
Boyksen and Kotlik (2013, pp. 49-52)	G	•		•					-	-	-
Jäger *et al.* (2013, pp. 342-343)	PR, SC	•	•	•	•				-	-	-
Meier and Bojarski (2013, pp. 548-551)	G	•	•						+ +	+ +	-
Serdarasan (2013, pp. 537-538)	SC	•	•	•	•				-	-	-
Grimm, Schuller and Wilhelmer (2014, pp. 95-97)	G	•		•	•		•	•	-	-	-
Schöttl *et al.* (2014, pp. 258-259)	PR	•	•		•				-	+	-
Wassmus (2014, pp. 61-65)	G	•		•			•	•	+ +	-	-

Table 27: Overview about existing complexity management approaches – Evaluation according to specific criteria (Part A)

Explanation for focus:
G General in manufacturing companies
PD Product development
PC Procurement
PR Production
L Logistics
SC Internal supply chain
D Distribution

Explanation for evaluation criteria:
+ + fulfilled
\+ partially fulfilled
\- not fulfilled

Author(s)	**Focus**	**Evaluation criteria**											
		Recurring cycle	Modular structure	Practicability	Transparency	Identifying the complexity problem	Methods for complexity management	Application of key figures	Approach for capability planning	Identification of complexity drivers	Complexity driver's interdependencies	Evaluation of complexity drivers	Evaluation of complexity (degree)
Grossmann (1992, pp. 209-213)	G	-	-	+ +	+	+ +	+ +	+	-	-	-	-	-
Wildemann (1995, pp. 23-24)	PR	-	+ +	-	-	-	+ +	-	-	-	-	-	+ +
Fricker (1996, pp. 112-114)	G	-	-	+	+ +	+ +	+ +	-	-	+	-	-	-
Warnecke and Puhl (1997, pp. 360-362)	G	+ +	+	+ +	+	-	+ +	-	-	+ +	-	+ +	+ +
Bliss (1998, pp. 151-164)	G	+ +	-	+ +	+	-	+ +	-	-	-	-	-	+
Bohne (1998, pp. 91-92)	G	+	-	+	+ +	+	+ +	-	-	-	-	-	-
Rosemann (1998, pp. 60-62)	G	-	-	+	-	-	+ +	-	-	-	-	-	-
Puhl (1999, pp. 45-97)	G	+ +	+ +	+ +	+ +	+	+ +	+	-	+	+	+	+ +
Wildemann (1999a, pp. 66-67)	PC	-	-	+ +	-	-	+ +	-	-	-	-	-	-
Bliss (2000, pp. 194-208)	G	+ +	-	+ +	+	-	+ +	-	-	-	-	-	+
Westphal (2000, p. 28)	L	-	-	-	-	-	+ +	-	-	-	-	-	-
Miragliotta, Perona and Portioli-Staudacher (2002, pp. 382-383, 388-392)	G	+	-	+	+ +	-	-	-	-	+	+	-	+
Kim and Wilemon (2003, pp. 24-27)	PD	+	-	+	+ +	+	-	+	-	+	-	+	-
Kirchhof (2003, pp. 167-243)	G	+	+	-	+ +	-	+	-	-	+ +	+ +	+	-
Dehnen (2004, pp. 49-61)	PD	-	+	+	-	-	+	-	-	-	-	-	+
Hanenkamp (2004, pp. 59-138)	PR	+	+	-	+ +	-	+	-	-	+ +	+ +	+	-
Meier and Hanenkamp (2004, pp. 118-127)	SC	+ +	+	+ +	+	-	+ +	-	-	+ +	-	+ +	-
Perona and Miragliotta (2004, pp. 112-114)	PR, L	-	-	+	+ +	-	-	-	-	-	-	-	-
Blecker, Kersten and Meyer (2005, pp. 51-52)	G	+	+	+ +	+ +	-	-	-	-	+ +	+ +	-	-
Geimer (2005, pp. 45-46)	SC	-	-	-	+ +	+	+ +	-	-	+	-	-	-
Geimer and Schulze (2005, p. 102)	SC	-	-	+	+ +	+	+ +	-	-	+	-	-	-
Anderson *et al.* (2006, p. 21)	G	-	-	-	+	-	-	-	-	-	-	-	-
Greitemeyer and Ulrich (2006, p. 8)	G	-	-	+	+ +	-	-	+	-	-	-	-	+
Denk (2007, pp. 20-21)	G	-	+	-	+ +	-	-	-	-	-	-	-	-

Table 27: Overview about existing complexity management approaches – Evaluation according to specific criteria (Part B)

Explanation for focus:
G General in manufacturing companies
PD Product development
PC Procurement
PR Production
L Logistics
SC Internal supply chain
D Distribution

Explanation for evaluation criteria:
+ + fulfilled
+ partially fulfilled
- not fulfilled

Author(s)	Focus	Evaluation criteria: Recurring cycle	Modular structure	Practicability	Transparency	Identifying the complexity problem	Methods for complexity management	Application of key figures	Approach for capability planning	Identification of complexity drivers	Complexity driver's interdependencies	Evaluation of complexity drivers	Evaluation of complexity (degree)
Marti (2007, pp. 152-153)	G	-	-	+ +	+ +	-	+	-	-	-	-	-	+
Meyer (2007, pp. 129-142)	D	+ +	+ +	+ +	+ +	-	+ +	+	-	+ +	+ +	+	-
Bick and Drexl-Wittbecker (2008, pp. 78-81)	G	-	-	+	+	+	+	-	-	-	-	-	-
Schuh *et al.* (2008, pp. 447-448)	G	-	+	-	+	+	-	-	-	-	-	-	-
Denk and Pfneissl (2009, pp. 28-32)	G	-	+	-	+ +	-	-	-	-	-	-	-	-
Lasch and Gießmann (2009b, pp. 114-118)	G	+ +	-	+	-	+	+ +	+	-	+ +	+ +	+	+
Lindemann, Maurer and Braun (2009, pp. 61-66)	PD	-	-	-	+	+	+	-	-	-	-	-	-
Blockus (2010, pp. 269-293)	G	-	-	+	+ +	-	+	+	-	-	-	-	-
Warnecke (2010, p. 641)	G	-	-	+	+	-	+	-	-	-	-	-	+
Isik (2011, pp. 422-423)	SC	-	-	+	+ +	+	-	-	-	+	+	-	-
Kersten (2011, pp. 15-18)	SC	-	-	+	+	-	+	-	-	+ +	+	-	-
Schawel and Billing (2011, pp. 110-111)	G	-	-	+	+ +	-	+ +	-	-	+ +	+ +	+	-
Fabig and Haasper (2012, pp. 17-19)	G	+	-	-	-	-	+	-	-	-	-	-	-
Koch (2012, p. 54)	G	-	-	-	+	-	-	-	-	-	-	-	-
Lammers (2012, pp. 85-135)	D	-	-	+	+ +	+	+ +	-	-	+ +	+ +	+ +	-
Aelker, Bauernhansl and Ehm (2013, pp. 81-82)	SC	-	-	-	+	-	-	-	-	+	-	-	+
Boyksen and Kotlik (2013, pp. 49-52)	G	+ +	-	+	+	-	-	-	-	+	-	+	+
Jäger *et al.* (2013, pp. 342-343)	PR, SC	+	-	-	+	-	-	+	-	+	-	-	+
Meier and Bojarski (2013, pp. 548-551)	G	+	+	+	+ +	-	+	-	-	-	-	-	-
Serdarasan (2013, pp. 537-538)	SC	+ +	+	-	+	-	-	-	-	+	-	-	+
Grimm, Schuller and Wilhelmer (2014, pp. 95-97)	G	+	-	+	+	+	-	-	-	+	-	-	-
Schöttl *et al.* (2014, pp. 258-259)	PR	-	-	+	+	+ +	+	-	-	+	-	+ +	-
Wassmus (2014, pp. 61-65)	G	+ +	+	-	+	-	+	-	-	-	-	-	-

6.3 Complexity management in variant-rich product development

In our literature review, we identified 7 stages, which were applied for complexity management in the company. Product development is characterized by variety, dynamics, complex and nontransparent tasks and uncertain processes (Wildemann, 2012, p. 202; Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386; Specht and Beckmann, 1996, pp. 25-26). This leads to an increasing risk in product development (Specht and Beckmann, 1996, p. 25). For risk management, 4 stages are described in literature: Analysis, evaluation, regulation and controlling of risks (Ahrendts and Marton, 2008, p. 14; Schawel and Billing, 2011, p. 165). Complexity and risk are closely connected, because of their characteristics (Specht and Beckmann, 1996, pp. 25-26). Thus, risk management's 4 stages can also be applied for complexity management.

Considering product development's characteristics, we developed a 4-stage complexity management approach for variant-rich product development based on the existing literature and the risk management strategies (see Figure 21). The approach is focused on product development's 3 main dimensions product complexity, product portfolio complexity and process complexity (Dehnen, 2004, p. 9) and comprises the 7 stages. The approach is designed as a recurring cycle with a modular structure to fulfill the structural requirements of a complexity management approach. Furthermore, different methods and tools for complexity management are described to gain practicability.

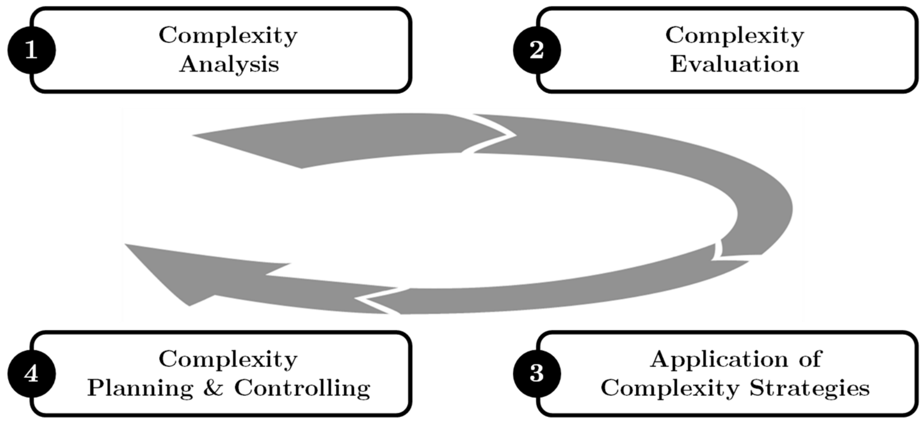


Figure 21: Four stage complexity management approach

The new approach was applied on a recent development project in the automotive industry to verify the scientific results. Cars are probably the most complex mass-produced industrial products on the market, because they combine many different parts, components, technologies and functions. The development process takes between 3 to 4 years and involves hundreds of engineers, technicians and partners (Moisdon and Weil, 1996, cited in Aggeri and Segrestin, 2007, p. 38). In the last years, automotive companies increased their product portfolio successively to gain market shares and to be competitive. Complex products, such as cars, consist not only of mechanical and electrical parts and components, but also of software, control modules and human-machine interfaces (ElMaraghy *et al.*, 2012, p. 793), which influence each other and lead to increasing complexity.

6.3.1 Stage 1 – Complexity analysis

Complexity in a project, especially in product development, requires a detailed complexity analysis (Warnecke, 2010, p. 640) to increase transparency and to fulfill the functional requirements (see subsection 6.2.1). The first step is to formulate and distinguish the tangible problem and to derive the demand for action (Grossmann, 1992, p. 209; Fricker, 1996, p. 113; Schöttl *et al.*, 2014, p. 258). Hauschildt (1977, p. 127) argues that a problem's complexity is related to a problem's structure, its parts and uncertainty. For analyzing the complexity problem, Schöttl *et al.* (2014, p. 258) use individual questionnaires. The second step is to identify and analyze the complexity drivers. Complexity driver's analysis and understanding is the basis for developing a clear strategy for managing complexity (Serdarasan, 2013, p. 533). In literature, several approaches for complexity driver's identification exist. The most applied approaches are expert interviews, process or systems analysis and influence analysis. In the third step, product variants are analyzed in detail to identify product's commonalities and differences and to identify the main attributes, which characterize a product variant. Variant's analysis and the main attributes are the basis for generating a variant derivation matrix in terms of an effective variant management (Nurcahya, 2009, pp. 59-68). Variants are products with a high proportion of identical components in the categories geometry, material or technology (Lingnau, 1994, p. 24). DIN 199 (1977 cited in Schwenk-Willi, 2001, pp. 22-23) defines variants as objects with a similar form or function and a high proportion of identical groups or components.

In our case study, the investigated object was the powertrain of a car. To identify the complexity problem in the product development department, we used expert interviews and questionnaires. The result was that the product portfolio increased continuously over the last years to gain market shares. However, the available budget and the development time for projects are decreasing successively. Another problem is that the variants are characterized by different complexity levels. Thus, the management is faced to develop an increased powertrain product portfolio in less time with the same or less input and resources. For a detailed problem and complexity analysis, the powertrain was abstracted to a product model (see Figure 22) (Nurcahya, 2009, pp. 59-62). The product model is an abstraction of a real product and contains all relevant elements or modules for product's characterization (Nurcahya, 2009, pp. 54-61). This model is the basis for complexity driver's identification, analysis and evaluation. In our case study, the product model of a powertrain is divided into 5 main modules (1 - engine; 2 - induction system; 3 - fuel injection system; 4 - exhaust system; 5 - drivetrain) and contains 48 relevant elements (turbocharger, injection valve, catalytic converter, etc.).

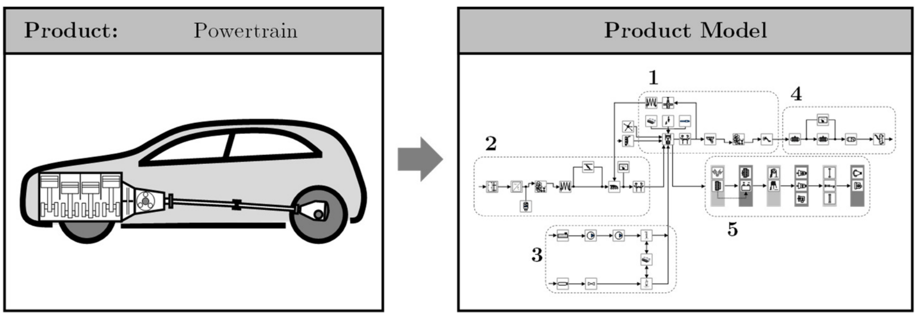


Figure 22: Powertrain product model

Next, the complexity drivers were identified and analyzed by using different approaches in the 3 categories product, product portfolio and process.

- Product: Literature analysis, expert interviews, questionnaires, workshops, influence analysis
- Product portfolio: Expert interviews, workshops, variant tree
- Process: Process analysis, expert interviews, workshops

In the third step, the product portfolio was analyzed to identify commonalities and differences. Based on product's and complexity driver's analysis, the main attributes, which characterize a product variant, were defined.

Product portfolio can be divided in reference variants, product variants, product groups and product families. The reference variant is the most complex variant within a product family and the basis for variant's derivation. Product variants are derived from reference variants and clustered within the product family. A product group consists of several product families. Within a product family, the variants are similar regarding specified criteria (Nurcahya, 2009, pp. 52-55). Next, all reference and product variants within a product family are compared according to their characteristics to identify commonalities and differences (Nurcahya, 2009, pp. 66-67). Nurcahya developed a matrix for variants' comparison. The matrix shows, which variants have the same characteristics and can be derived from another.

In our case study, a powertrain variant can be described by 20 different attributes (e.g. engine, transmission, time to market, etc.). Within the attributes, different product variants exist (e.g. 3.0l, 2.5l or 2.0l engine; automatic or manual transmission; etc.). According to product complexity, development effort and time to market, the most complex and expensive product in the product portfolio, launched first in market, is the reference variant, called lead variant. Product variants, which can be derived from a lead variant, are called derivates. According to their complexity, development effort and time to market, derivates can be further separated in different sizes, such as large, medium and small. As a result of this classification, a product portfolio can be clustered into 4 different groups: Lead [L], derivate large [DL], derivate medium [DM] and derivate small [DS]. Based on the described attributes, we analyzed and evaluated the product portfolio to identify commonalities and differences. Furthermore, we clustered the variants according to the product classification and developed a derivation matrix with expert's cooperation. Basically, the derivation matrix is similar to an influence matrix and shows, which variant can be derived from another. Figure 23 shows a derivation matrix for the main attributes "engine" (3.0l, 2.5l or 2.0l) and "transmission" (automatic or manual) and an example for clustering a product portfolio, consisting of 5 variants with different market launches. With the derivation matrix, the powertrain portfolio can be analyzed and clustered into the 4 different groups. In the example, the reference variant, called lead variant [L], is the powertrain with a 3.0l engine and an automatic transmission. The lead is the most complex variant, launched first in the market at the time of T0. All other variants are derivates from the lead variant with different sizes and launched after T0.

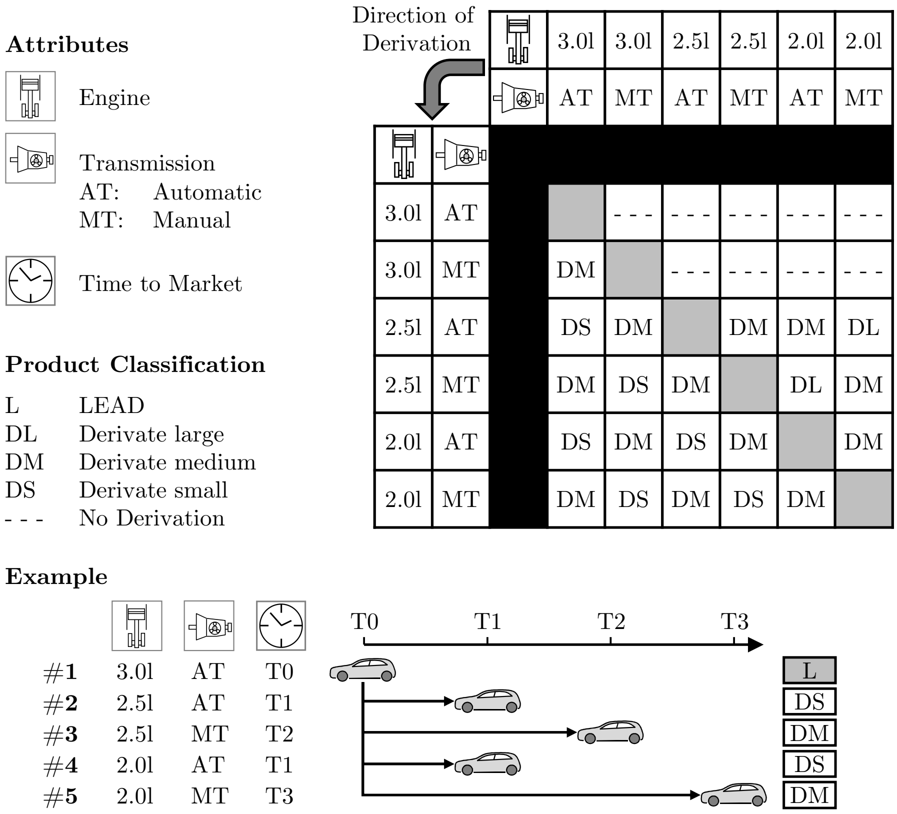


Figure 23: Derivation matrix and example

6.3.2 Stage 2 – Complexity evaluation

The second stage of our complexity approach comprises the complexity evaluation in the 3 categories product, product portfolio and process. The objective of evaluation in general is to emphasize commonalities and differences between relating object's properties (Kieser and Kubicek, 1983, p. 174). Beyond, complexity evaluation is the basis for application of the right complexity strategy in the next stage of our approach.

Complexity management's objective is to achieve a company's optimum complexity degree, where internal and external complexity are equal (Schuh, 2005, p. 43; Boyksen and Kotlik, 2013, p. 49; Reiß, 1993b, pp. 56-57). In product development, internal complexity is characterized by product, product portfolio and process complexity (Dehnen, 2004, pp. 33-35). External complexity is characterized by environmental, demand and competitive complexity (Dehnen, 2004, pp. 33-35). Thus, company's optimum complexity degree can be achieved by evaluating and managing internal complexity. According to systems theory, a system's complexity degree is characterized by the amount of elements, their dependencies and the amount of system's conditions, so called variety (Curran, Elliger and Rüdiger, 2008, p. 162; Malik, 2002, p. 186). Malik (2002, p. 186) argues that complexity can be quantified by variety. In literature, no uniform definition and measuring scale for a complexity degree exists. Höge (1995, pp. 31-32) and Greitemeyer and Ulrich (2006, p. 8) state that the optimum complexity degree and measuring scale must be planned company-specific according to each company's strategy. To achieve a company's optimum complexity, internal complexity must be analyzed and evaluated. In our case study, we developed 3 complexity indices based on variety to evaluate product development's internal complexity in the categories product, process and product portfolio. According to Kieser and Kubicek (1983), the objective is to compare different development projects in the categories to identify complexity trends over time.

6.3.2.1 Product complexity index (PDCI)

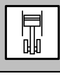
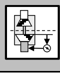
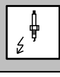
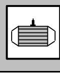
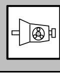
ElMaraghy and ElMaraghy (2014, p. 5) describe a product complexity index to characterize a product and to measure, how complex a product is. The measurement is based on variety. According to ElMaraghy and ElMaraghy, we also developed a PDCI based on the product and the difference of variety (ΔCn) within the identified product complexity driver's categories. In our evaluation, the complexity drivers were weighted according to development effort, costs and time (WF_{Cn}), because some drivers are more complex than others. The most complex drivers have the weighting factor 1.0. The weighting factors of other drivers are defined in comparison to the most complex driver.

The PDCI is formulated as the weighted average of variety difference in all product complexity driver's categories (Cn). N is the maximum amount of product complexity driver's categories and n is the category's number.

$$\mathrm{PDCI} = \frac{\sum_{n=1}^{N}(\Delta \mathrm{Cn} * \mathrm{WF}_{\mathrm{Cn}})}{\mathrm{N}}$$

The PDCI represents the percentage increase or decrease of development effort or costs, in comparison to the basis. Table 28 shows an example for calculating a PDCI of 2 powertrain development projects. Project #1 is already completed, while project #2 is currently developed. For comparison, we use 7 complexity driver's categories (C1 to C7): Engine (C1), turbocharger (C2), valve controlling (C3), fuel injection system (C4), ignition system (C5), catalytic converter (C6) and transmission (C7). In the first step, the variety in the categories C1 to C7 is identified for project #1 and #2. Next, the differences of variety (ΔCn) between project #1 and #2 are calculated, using project #1 as the basis. Then, PDCI's percental change is calculated considering different weighting factors. As a result, the new project #2 has a complexity increase of 40%, compared to project #1. In category 2 (C2) the variety of turbochargers in project #1 and #2 is identified. The finished project #1 had 1 turbocharger and the current project #2 has 2 different turbochargers. The difference (ΔCn) between project #2 and #1 is 1. The basis is project #1, thus the variety in project #2 increased by 100%. The categories turbocharger (C2) and valve controlling (C3) have a weighting factor of 1.0, because they are the most complex drivers.

Table 28: Example PDCI

PDCI	Product Complexity Driver's Categories *Cn*						
	C1 	C2 	C3 	C4 	C5 	C6 	C7 
Variety in *Cn* Project #1	2	1	1	2	1	2	1
Variety in *Cn* Project #2	2	2	3	1	1	1	2
$\triangle Cn_{\text{Project\#1}\rightarrow\#2}$	0%	+100%	+200%	-50%	0%	-50%	+100%
Weighting factor WF_{Cn}	0.8	1.0	1.0	0.6	0.7	0.9	0.6
Result	**PDCI: +40%**						

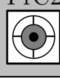
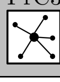
6.3.2.2 Process complexity index (PRCI)

In literature, no process complexity index exists. Thus, we developed a PRCI analogously to PDCI. PRCI is based on the development process and the difference of variety within the identified process complexity driver's categories ($\triangle PrCn$). The complexity drivers were also weighted according to development effort and time (WF_{PrCn}). The PRCI is formulated as follows:

$$\text{PRCI} = \frac{\sum_{n=1}^{N}(\Delta\text{PrCn}*\text{WF}_{\text{PrCn}})}{\text{N}}$$

Table 29 shows an example for calculating a PRCI of 2 powertrain development projects. In this case, the process complexity drivers are the amount of different process steps (PrC1), their conjunctions (PrC2) and the amount of interfaces to other subsections within the value chain (PrC3). The PRCI is calculated analogously to PDCI. As a result, the development process of project #2 has a complexity increase of 26%, compared to project #1.

Table 29: Example PRCI

PRCI	Process Complexity Driver's Categories *PrCn*		
	PrC1 	PrC2 	PrC3 
Variety in *PrCn* Project #1	6	2	5
Variety in *PrCn* Project #2	7	3	6
$\triangle PrCn_{\text{Project\#1}\rightarrow\#2}$	+17%	+50%	+20%
Weighting factor WF_{PrCn}	0.7	1.0	0.8
Result	**PRCI: +26%**		

6.3.2.3 Product portfolio complexity index (PPCI)

Product portfolio complexity is another important part, when evaluating product development's complexity. However, in literature no index for measuring product portfolio's complexity exists. Based on product attributes (e.g. engine or transmission), product classification (e.g. lead or derivates) and derivation matrix, the product portfolio can be analyzed and clustered into different groups (leads and derivates) according to their characteristics. Next, the groups with equal product classifications are evaluated by the assignment of weighting factors. The weighting factors are also defined according to development effort, costs and time and represent single efforts. The lead variant is the most complex and expensive variant with the highest single effort and has the weighting factor 1.0. The weighting factors of the derivates (large, medium and small) are defined in comparison to the lead variant.

The PPCI is calculated by summing up the weighting factors ($WF_{Variant\ n}$), which were assigned to all variants in the product portfolio. N is the total amount of product variants in the product portfolio and n is the product variant's number. PPCI's unit are effort points [EP].

$$\mathrm{PPCI} = \sum_{n=1}^{N} \mathrm{WF}_{\mathrm{Variant\ n}}$$

PPCI facilitates product portfolio's standardization to one measured value considering product and process complexity and provides an overview about complexity in the product portfolio. Furthermore, PPCI describes the total effort, which is dedicated to develop a specific product portfolio. To quantify product portfolio's complexity in our case study, we developed 4 weighting factors for our product classifications according to their complexity, development time and effort. The lead variant is the most complex variant in the portfolio and has the highest factor 1.0. The derivates have weaker factors. Figure 24 shows an example for calculating the PPCI for a product portfolio with 5 powertrains.

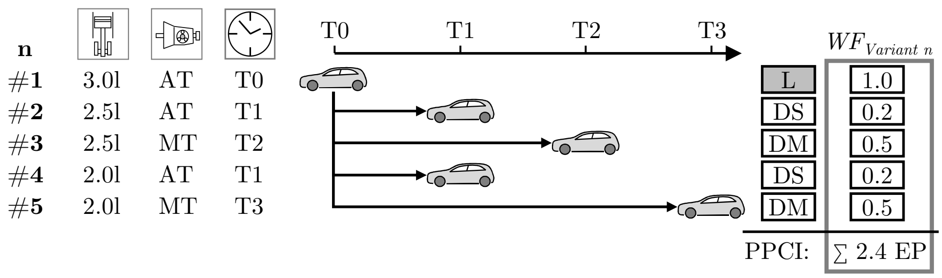


Figure 24: Example for calculating a PPCI

In the next step, product's development effort is identified and evaluated over product's launch time. The PPCI and the evaluated product portfolio are the basis for calculation. Therefore, the development efforts over time for the different product classifications (Lead or Derivate) were described. In our case study, the development efforts of a lead variant were separated evenly over a period of 3 years. The time period is determined by company's experts. They divide the development efforts in different periods according to their development plan. The development efforts for our derivates were specified analogously. However, the periods were 1 year for small and 2 years for medium and large derivates. For calculation of the total development effort in a period, the particular efforts were summed-up. Figure 25 shows an example for calculating the development effort over time for a product portfolio consisting of 5 powertrains. It can be seen that the maximum is in period D, because of the amount of variants, which are developed simultaneously. Furthermore, the PPCI can also be calculated as a number, called effort points [EP].

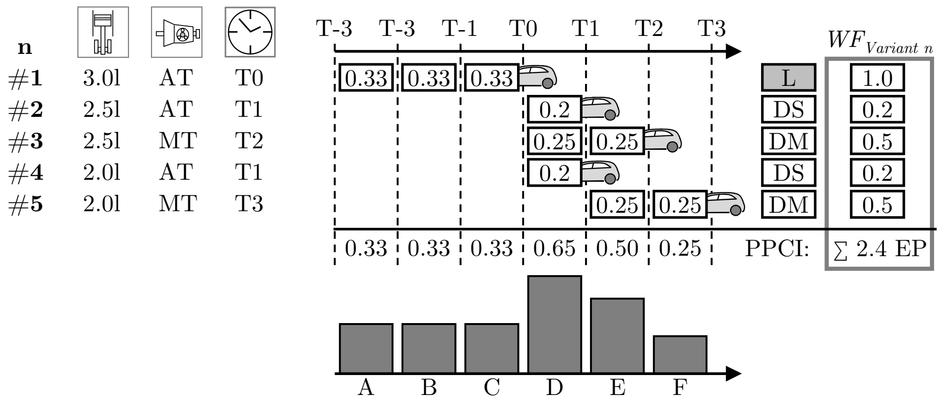


Figure 25: Calculating project's development effort over time

6.3.3 Stage 3 – Application of complexity strategies

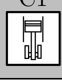
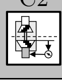
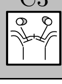
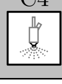
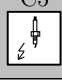
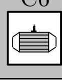
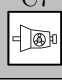
In the third stage, the complexity strategies are presented for company's complexity optimization. In literature, a vast number of different single approaches for managing complexity are described (Gießmann, 2010, pp. 57-70). However, there is no specific instruction, which approaches are the most effective for managing a specific complexity problem. Approach's application depends on the particular situation and must be planned company-specific. Generally, the approaches can be divided in 4 categories according to their focus: Product, product portfolio, process and organization (Gießmann, 2010, pp. 57-70). The approaches are mainly used for complexity reduction, mastering and avoidance. Table 30 presents an overview about the different approaches and their main purposes. The basis for Table 30 was our literature analysis.

Table 30: Applied single approaches for complexity management

Focus	Approaches	Complexity strategies		
		Reduction	Mastering	Avoidance
Product	Modular concept	+ + +	+ +	+
	Modular system	+ + +	+ +	+
	Standardization	+ + +	+	+ +
	Using same parts	+ + +	+	+ +
	Platform concept	+ + +	+ +	+
	Differential construction	+ + +	+ +	+
	Integral construction	+ + +	+ +	+
Product portfolio	Packaging	+ + +	+ +	
	Reducing product range	+ + +		+ +
	Reducing of customers	+ + +		
Process	Postponement concept	+ + +	+ +	+
	Standardization of processes	+ + +		+ +
	Modularity of processes	+ + +	+ +	+
Organization	Delayering	+ + +		
	Empowerment	+ + +		
Explanation	+ + + Priority 1 + + Priority 2 + Priority 3			

In our research project, we applied different single approaches for complexity reduction, mastering and avoidance in the categories product, product portfolio and process. The effects resulting of an approach's application are evaluated with our 3 indices to identify the approach's effectivity. Table 31 and Table 32, as well as Figure 26 show 3 examples from our research project. In the first example (see Table 31), we use product standardization to reduce the variety in the categories turbocharger (C2) and valve controlling (C3) in project #2. After product standardization, the current development project has 1 turbocharger and 2 valve controlling systems. Thus, the PDCI was reduced from 40% to 12%.

Table 31: Application of product standardization, focused on PDCI

PDCI Product standardization in the categories C2 and C3	Product Complexity Driver's Categories *Cn*						
	C1 	C2 	C3 	C4 	C5 	C6 	C7 
Variety in *Cn* Project #1	2	1	1	2	1	2	1
Variety in *Cn* Project #2	2	~~2~~ 1	~~3~~ 2	1	1	1	2
$\triangle Cn_{\text{Project\#1}\rightarrow\#2}$	0%	0%	+100%	-50%	0%	-50%	+100%
Weighting factor WF_{Cn}	0.8	1.0	1.0	0.6	0.7	0.9	0.6
Result	**PDCI:** +~~40%~~ ➔ +**12%** (Complexity Reduction)						

Next, process standardization and modularization were applied in category PrC1 (see Table 32). Different process steps were standardized and modularized to reduce the number from 7 process steps to 5. The PRCI was reduced from 26% to 18%.

Table 32: Application of process standardization and modularization, focused on PRCI

PRCI Process standardization and modularization in the category PrC1	Process Complexity Driver's Categories *PrCn* PrC1	PrC2	PrC3
Variety in *PrCn* Project #1	6	2	5
Variety in *PrCn* Project #2	**~~7~~ 5**	3	6
$\triangle PrCn_{\text{Project\#1}\rightarrow\#2}$	**-17%**	+50%	+20%
Weighting factor WF_{PrCn}	0.7	1.0	0.8
Result	**PRCI:** +~~**26%**~~ ➔ **+18%** (Complexity Reduction)		

In the third example, we reduced product portfolio's complexity, development efforts and costs by reducing the product range (see Figure 26). Based on a cost-benefit analysis, company's experts decided to remove the variants #3 and #4 with weighting factors of 0.5 and 0.2 from the product portfolio. The PPCI was decreased from 2.4 to 1.7 effort points. In period D and E, the development effort also decreased from 0.65 EP (period D) and 0.5 EP (period E) to 0.20 EP (period D) and 0.25 EP (period E).

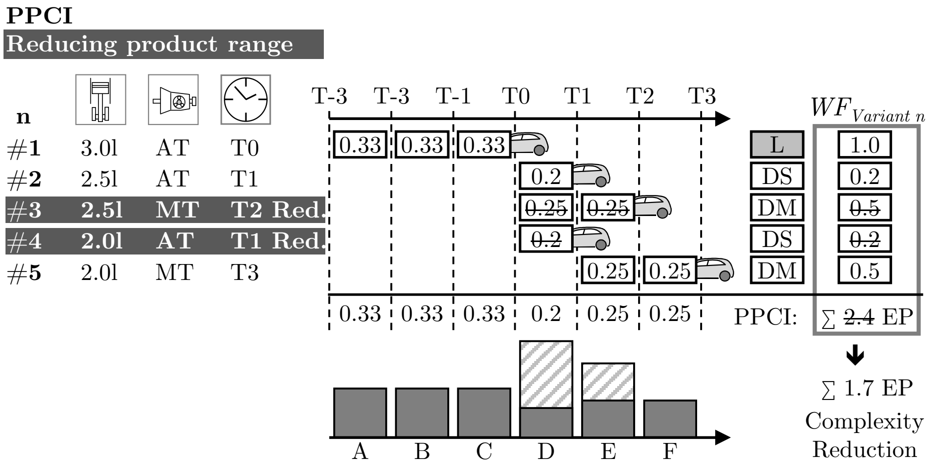


Figure 26: Application of 'reducing product range', focused on PPCI

6.3.4 Stage 4 – Complexity planning and controlling

Complexity planning and controlling are important elements for a target-oriented complexity management. They provide a leverage point for an active complexity adjustment and help the company to prevent costs (Kirchhof, 2003, pp. 166-167). Company's capacity planning contains planning of resources (Schuh, Millarg and Göransson, 1998, p. 49) and is an important factor for company's competitiveness (Krüger and Homp, 1997, p. 10). Furthermore, it is the basis for complexity controlling (Jania, 2004, p. 16). Resources can be separated in tangible (e.g. equipment, facility) and intangible (e.g. technology, image) resources (Hungenberg, 2001, p. 116). To reduce costs and time, it is necessary to apply the resources efficiently. In product development, resources have a particular relevance, because the amount of available resources is restricted. Based on our research, product development's complexity has a high influence on the required resources and their planning. A detailed complexity planning increases transparency and enables the management to simulate different development scenarios to identify the optimum.

Complexity costs can be separated into direct and indirect costs. Direct costs consist of continuous (e.g. costs for serial supervision) and nonrecurring costs (e.g. test vehicle, test engine). Indirect costs are costs, which generate no benefit growth (e.g. costs for increasing product range have no benefit, because of product cannibalization) (Gießmann, 2010, p. 39).

In our research project, we developed a complexity planning model based on literature and the results of complexity analysis and evaluation. The complexity indices are particularly important for this.

Kersten, Lammers and Skirde (2012, pp. 28-30) developed a complexity vector with 2 dimensions for complexity driver's visualization and operationalization. The dimensions describe different points of view regarding complexity's occurrence and can be weighted. Different complexity drivers can be visualized in the vector space and can thereby be compared with each other. The visualization can be used as a starting point for different strategies in complexity management. According to Kersten, Lammers and Skirde (2012), we developed a complexity vector $\overrightarrow{\mathrm{CI}}$ with the 2 dimensions product complexity index (PDCI) and process complexity index (PRCI). The 2 dimensions have the same weighting.

$$\overrightarrow{\mathrm{CI}} = \binom{\mathrm{PDCI}}{\mathrm{PRCI}}$$

Vector $\overrightarrow{\mathrm{CI}}$ is visualized in the vector space. Vector's length $|\overrightarrow{\mathrm{CI}}|$ represents development project's complexity. The distance between 2 complexity vectors describes the proportion of complexity reduction. The distance is calculated with Pythagoras' theorem.

$$|\overrightarrow{\mathrm{CI}_{12}}| = \sqrt{(\mathrm{PDCI}_1\text{-}\mathrm{PDCI}_2)^2+(\mathrm{PRCI}_1\text{-}\mathrm{PRCI}_2)^2}$$

In the first step of our complexity evaluation, we identified a $PDCI_1$ with 40% and a $PRCI_1$ with 26% (see subsection 6.3.2) and generated the vector $\overrightarrow{\mathrm{CI}_1}$ (see Figure 27). After complexity evaluation, we applied different single approaches to reduce the complexity indices (see subsection 6.3.3). PDCI_2 (12%) and PRCI_2 (18%) are the basis of vector $\overrightarrow{\mathrm{CI}_2}$. The distance between $\overrightarrow{\mathrm{CI}_1}$ and $\overrightarrow{\mathrm{CI}_2}$ is the proportion of complexity reduction. In our case study, the application of different single sources resulted in a complexity reduction of 29% in total.

For complexity planning, the length of $\overrightarrow{\mathrm{CI}_2}$ is important, because it is directly associated to development project's complexity, development efforts and the amount of required resources (see Figure 27). Thus, the amount of required resources is directly proportional to the length of $\overrightarrow{\mathrm{CI}_2}$ and the PPCI. The length of $\overrightarrow{\mathrm{CI}_2}$ is 22%, thus the amount of resources in the periods A until F are also increased by this percentage.

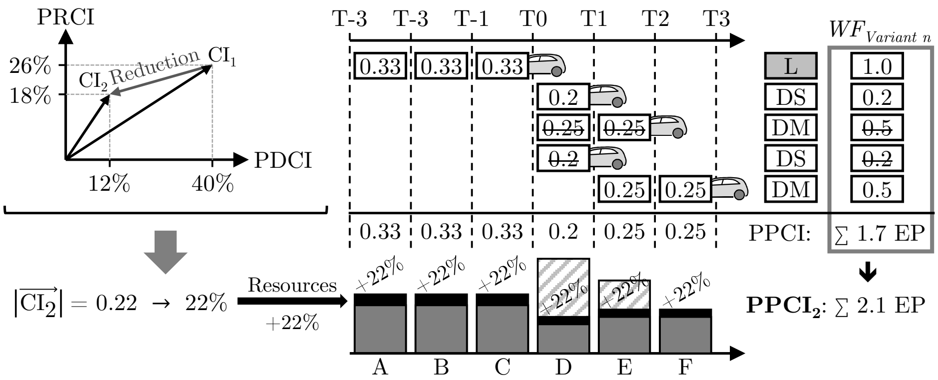


Figure 27: Complexity vector's influence on development effort

For calculating the precise amount of required resources (e.g. test vehicles), we determined a resource factor (RF) based on process analysis, expert interviews and workshops (e.g. 7 test vehicles per effort point). The resource factor represents the amount of resources, which are required for a specific development effort. With the resource factor, the development efforts [EP] in each period can be translated in a precise amount of required resources. In Figure 28, we calculated the amount of test vehicles in period A based on the amount of effort points in period A and the resource factor for test vehicles. The calculation is based on Figure 27. This procedure was used analogously to develop cost factors for calculating development costs.

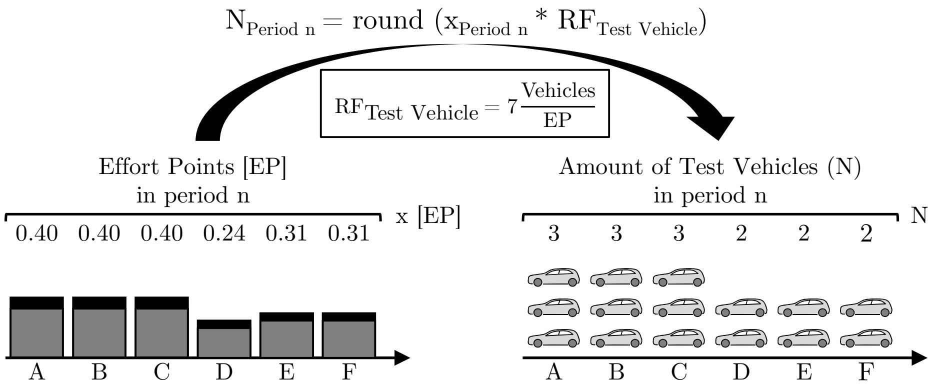


Figure 28: Calculating required resources based on resource factor

In product development, complexity controlling enables the management to compare the actual development efforts or costs of different projects with the planned values to identify weaknesses, potentials and to influence company's development activities. The objective is to develop a complexity controlling system to fulfill these requirements and to provide a methodical principle (Jania, 2004, pp. 15-17). For complexity controlling, key performance indicators (KPIs) were used to gain transparency and to apply specific strategies in product development. KPIs in different projects or function levels can be compared with reference values to identify discrepancies and increasing complexity (Gleich and Klein, 2013, pp. 49-53). Furthermore, KPIs are used to achieve company's objectives and are defined company specific (Kersten, 2011, p. 17). KPIs can be defined by comparison of costs and benefits (Gleich and Klein, 2013, p. 53). Based on Kersten, Gleich and Klein (2013), we developed a project KPI ($KPI_{Project\ n}$) by comparing the applied amount of resources ($N_{Resources\ Project\ n}$) and project's PPCI. KPIs are compared with reference values to identify discrepancies.

$$\mathrm{KPI}_{\mathrm{Project\ n}} = \frac{\mathrm{N}_{\mathrm{Resources\ Project\ n}}}{\mathrm{PPCI}_{\mathrm{Project\ n}}}$$

Figure 29 shows an example with 2 projects (A and B) in period A. The projects have different PPCIs, but the amount of applied resources (test vehicles) is equal. To compare the projects, the project KPIs for A and B are determined and compared with the reference value. In our case study, the reference is the resource factor for test vehicle. As comparison's result, project A is more efficient than project B ($\mathrm{KPI}_{\mathrm{Project\ A}} < \mathrm{KPI}_{\mathrm{Project\ B}}$). However, both projects show differences according to the reference value. If the reasons for the differences are unclear, a further complexity analysis in stage 1 can be started. With this method, other KPIs can be developed analogously, such as for test engines or development costs.

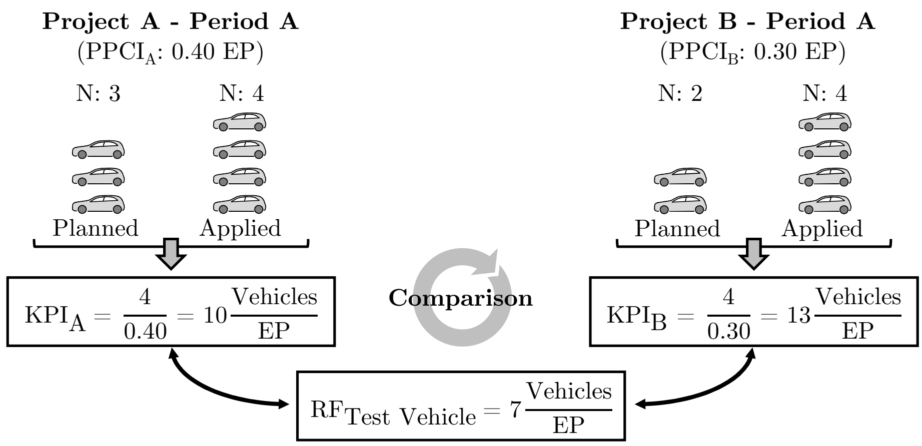


Figure 29: Calculating KPIs and comparison with reference values

6.4 Results and discussion

The result of this chapter is a 4-stage praxis-oriented approach for managing complexity in variant-rich product development. The approach was developed based on a detailed literature analysis and applied on a recent development project in the automotive industry. This chapter describes the objectives and requirements of complexity management approaches and characterizes the product development by the following 3 categories: Product, product portfolio and process. Based on these categories, the complexity drivers are derived and described. For this research, we determined 2 research questions, which will be answered in the following manner. Before developing a new approach, the existing literature must be identified, analyzed and evaluated systematically (**RQ1**). The identified approaches are analyzed according to their structure and focuses (**RQ2**). In literature, 47 complexity management approaches exist. However, an approach, which fulfills all requirements in total or partially does not exist yet.

In summary, our approach applies all steps and categories and fulfills all requirements in total (see Table 33). In all stages, we described different methods, which can be applied easily by the user. The new approach consists of a modular structure and a recurring cycle. The approach is focused on the 3 categories product, product portfolio and process and enables a detailed complexity analysis by identifying the complexity problem, the complexity drivers and their interdependencies (see subsection 6.3.1). After complexity analysis, project's complexity is evaluated and optimized by applying different complexity single approaches (see subsection 6.3.2 and 6.3.3). In the last stage, we developed an approach for capability and resource planning, as well as complexity controlling by the application of key performance indicators (KPIs).

Table 33: Evaluation of our new complexity management approach

Evaluation of the new complexity management approach for variant-rich product development																					
Approach's structure							Target			Evaluation criteria											
Complexity analysis	Complexity evaluation	Determine complexity strategy	Determine complexity instruments	Complexity planning	Implement complexity management	Complexity controlling	Product complexity	Process complexity	Product portfolio complexity	Recurring cycle	Modular structure	Practicability	Transparency	Identifying the complexity problem	Methods for complexity management	Application of key figures	Approach for capability planning	Identification of complexity drivers	Complexity driver' s interdependencies	Evaluation of complexity drivers	Evaluation of complexity (degree)
●	●	●	●	●	●	●	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++

Explanation:
● The new complexity management approach comprises the following content
++ The new complexity management approach fulfills the following requirement

6.5 Conclusion

This chapter's purpose was to close the research gap by analyzing existing literature and developing a praxis-oriented complexity management approach for variant-rich product development. In literature, such an approach does not exist yet. The existing approaches are focused on specific issues and do not fulfill all requirements in total or partially. This research covers this literature gap. It provides a 4-stage complexity management approach and encourages the reader to manage product development's complexity. The approach was first applied in the automotive industry and was verified in the toy industry. Future research may include other sectors.

7 Complexity management approach for resource planning in variant-rich product development

7.1 Introduction

„*Any customer can have a car painted any color that he wants so long as it is black.*“
Henry Ford

This famous statement by Henry Ford describes a time, where the fulfillment of individual customer wishes was not even up for debate (Kesper, 2012, p. 1). Ford established the mass production in the automotive industry between 1911 and 1914 and hereby initiated the change from customer-individualized cars to standardized mass products (Lasch and Gießmann, 2009a, p. 195). One hundred years later, customer's requirements and their position of power have increased strongly. The challenge of the 21st century has become producing and providing individualized and complex products by the use of standardized, lean and complexity reduced processes (Lasch and Gießmann, 2009a, p. 195). During the last years, continuous customer's requirements for individualized products and the increasing dynamics in innovation and technology lead to an increased product variety and complexity in many industrial branches. Furthermore, markets are changing from sellers to buyers markets, caused by differentiated customer requirements and heterogeneity and the resulting necessity to create more individualized products (Wildemann, 2005, p. 34; Schuh, Arnoscht and Rudolf, 2010, p. 1928). Today, manufacturing companies have changed their product portfolio from "standard, high-volume products to more exotic, low-volume products and product variants" (Götzfried, 2013, p. 31). For company's success, it is fundamental to bring new products quickly to the market (Augusto Cauchick Miguel, 2007, p. 617) and with customized settings (Lübke, 2007, p. 2).

When translating this principle to the automotive industry, for company's success and to be competitive, the automotive manufacturers have to bring innovative, individualized and complex cars in high quality and at low costs quickly to the market (Klug, 2010, p. 41). Globalization, internationalization, individualization and new technologies are reasons for the increasing product variety in the automotive industry (Klug, 2010, p. 41; Schoeller, 2009, p. 1). Furthermore, the requirements for electronical devices, safety and comfort lead also to an increase in product variety and complexity. In the strategic product planning of an automotive company, niche vehicles gain more and more importance, because new and smaller market segments have to be attended to (Klug, 2010, p. 41). Simultaneously, the innovation cycles have to be shortened due to market dynamics and lead to a further increase of complexity within the companies (Schoeller, 2009, p. 1). Another important factor that is currently being discussed is the fulfillment of legal environmental standards by the automotive manufacturers.

Due to the growing legal and social requirements, the companies have to accept the challenge to produce environmentally friendly cars and engines. Therefore, the fulfillment of legal environmental standards becomes a competitive factor. The manufacturers are forced to ensure the environmental compatibility of their products by developing new innovations (Ruppert, 2007, p. 80). As a result of this, more and more country and technological specific parts and products have to be developed and produced. This leads to an increased effort in product development and production (Klug, 2010, p. 41) and in resource application. In production, the amount of different product variants, caused by customer's requirements, determines an increase of required resources (Hanenkamp, 2004, p. 9). In product development and other parts of the value chain, the amount of required resources is also associated with the amount of different product variants. For example, procurement's effort is also connected with the amount of required resources. Thus, it is important that variant's appearance occurs at the end of the value chain (Franke and Firchau, 2001, p. 9).

Product development is one of the most complex and nontransparent tasks and uncertain processes within the company and is confronted with several complexity factors, such as demand variety, uncertain objectives, environmental dynamics, high time pressure and restricted resources (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386; Specht and Beckmann, 1996, pp. 25-26; Wildemann, 2012, p. 202). Product development's complexity is caused by a variety of internal and external sources, called complexity drivers (Dehnen, 2004, pp. 33-35). Complexity drivers describe a system's complexity and help to evaluate and handle it (Vogel and Lasch, 2015, pp. 98-99). Complexity management is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). Complexity, variety and the use of resources are closely connected. The complexity level has a high influence on the amount of required resources (Bohne, 1998, pp. 9-10). Thus, an approach that combines resource planning and complexity is required.

The purpose of this chapter is to present a praxis-oriented complexity management approach for resource planning in variant-rich product development. The resource planning comprises the quantitative planning of human and material resources over time. The approach was developed based on literature and encourages the reader to calculate the required resources within a variant-rich development project, for example in the automotive industry. Section 7.2 gives a literature overview about the properties, requirements and objectives on the issues complexity management, product development and resource planning. Furthermore, an overview of existing complexity management approaches and their applicability for resource planning in different fields is presented. As a result of the analysis of the existing complexity management approaches, only 1 complexity management approach comprises a methodology for resource planning. Based on the existing methodology, a new complexity management approach for resource planning in variant-rich product development was developed and described in section 7.3. Furthermore, the new approach is applied on a recent development project for hybrid powertrains in the automotive industry. Section 7.4 concludes the chapter and closes the research gap with implications for future research.

7.2 Literature review

7.2.1 Complexity management

The origin of the term complexity comes from the Latin word "complexus", which means "extensive, interrelated, confusing, entwined or twisted together" (Pfeifer *et al.*, 1989, p. 889; Grübner, 2007, pp. 40-41; Gießmann, 2010, p. 30; ElMaraghy *et al.*, 2012, p. 794; Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). This is similar to the Oxford Dictionaries (2014) definition of "complex": Something is complex if it is "consisting of many different and connected parts" and it is "not easy to analyze or understand". Based on systems theory, complexity is characterized by the amount and diversity of system's elements, the amount and type of dependencies, as well as the variation of the elements and their dependencies over time (Kersten, 2011, p. 15). According to Schuh (2005), complex systems are characterized by the variety of their states (Schuh, 2005, pp. 34-35). Complexity is a phenomenon and evolutionary process, which presents a challenge, especially for science and engineering. Complexity is characterized through change, choice and selection, as well as perception and progress. Furthermore, complexity is intensified through innovations in products and processes (Warnecke, 2010, p. 639).

Complexity has been discussed in several fields of research, such as physics, biology, chemistry, mathematics, computer science, economics, engineering and management, as well as philosophy (Isik, 2010, p. 3682; Bozarth *et al.*, 2009, p. 79). In scientific literature, there are many different definitions for the term "complexity", because the meaning is vague and ambiguous. There is no explicit, universal and widely accepted definition (Riedl, 2000, pp. 3-7; Brosch and Krause, 2011, p. 2; ElMaraghy *et al.*, 2012, p. 794). As a result, the term "complexity" is often used synonymously with the term "complicated" (Gießmann, 2010, p. 30). According to Meijer (2006, p. 1), "complexity is in the eye of the beholder". Complexity is driven by the sensation or perspective of an individual. What is complex to someone, might not be complex to another (Leeuw, Grotenhuis and Goor, 2013, p. 961; Grübner, 2007, p. 41).

There are 2 types of complexity: Good and bad. The good type of complexity is necessary. It helps a company to gain market shares and is value adding. On the other hand, bad complexity brings little value, reduces revenue and causes excessive costs (ElMaraghy *et al.*, 2012, p. 811; Isik, 2010, p. 3681).

In scientific literature, increasing complexity is related to increasing costs (Meyer, 2007, p. 94). For example, additional costs are generated due to an increase of product and process variety, because of modifications in product design and processes, which may also have unpredictable effects on the whole product development process (Aggeri and Segrestin, 2007, p. 38). Managing a system's complexity requires an optimum fit between internal and external complexity (Schuh, 2005, pp. 34-35). According to Schuh (2005, p. 35), managing system's complexity comprises 4 tasks: Designing the necessary variety, handling variety-increasing factors, reducing variety and controlling complex systems. Generally, complexity is caused by internal and external factors, called complexity drivers (Meyer, 2007, pp. 26-27). Complexity drivers describe a system's complexity and help to evaluate and handle it (Vogel and Lasch, 2015, pp. 98-99). Complexity management is a strategic issue for companies to be competitive (Miragliotta, Perona and Portioli-Staudacher, 2002, p. 383). According to

ElMaraghy *et al.* (2012, p. 809), complexity management is a business methodology with the objective of complexity analysis and optimization within a company. In literature, complexity management has several objectives. The main objectives are complexity reduction, mastering and avoidance (Wildemann, 2012, p. 69; Lasch and Gießmann, 2009a, p. 198; Schuh and Schwenk, 2001, pp. 32-40; Kaiser, 1995, p. 102). Wildemann (2012, p. 69) defines these objectives as the 3 main strategies for complexity management in a company. Other important objectives are complexity identification and evaluation, as well as the determination of the optimum complexity degree (Krause, Franke and Gausemeier, 2007, pp. 15-16). Dehnen (2004, p. 99) argues further that complexity management's objective is to concentrate the available resources in an optimum way regarding company's strengths and weaknesses and market's opportunities and risks.

Complexity management requires approaches for complexity's understanding, simplification, transformation and evaluation (Hünerberg and Mann, 2009, p. 3). The objective of a successful complexity management approach is to ensure a balance between external market's complexity and internal company's complexity (Rosemann, 1998, p. 61; Kaiser, 1995, p. 17). For company's success, it is necessary to implement a complexity management in company's management process as an integrated concept (Kersten, 2011, pp. 17-18).

Today, complexity management is a very important issue for the automotive industry, because it is confronted with high complexity, costs and inefficiency along the value chain. Product complexity is the main complexity factor in the automotive industry (Schoeller, 2009, p. 6). Increasing complexity is one of the biggest challenges that manufacturing companies face today (ElMaraghy *et al.*, 2012, p. 793).

7.2.2 Product development

During the last years, complexity in product development, especially for complex products, has continuously increased, but has not been addressed in literature and practice satisfactorily yet (ElMaraghy *et al.*, 2012, p. 797). Firms in many industries are confronted with increasing global competition and changing market demands to bring innovative products in higher quality to the market more frequently (Ragatz, Handfield and Petersen, 2002, p. 389). For manufacturing companies, product development is an important source to be competitive and to gain a competitive advantage over other business firms (Schaefer, 1999, p. 311). Product development is one of the most complex and nontransparent tasks and uncertain processes in the company (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386; Specht and Beckmann, 1996, pp. 25-26). Product development's objective is "to translate an idea into a tangible physical asset" (Davila, 2000, p. 385). Further, product development's task is to develop new products for established markets (Bloech *et al.*, 1998, pp. 121-122). Krishnan and Ulrich (2001, p. 1) follow the definition of Davila and Bloech *et al.* and define product development as the "transformation of a market opportunity and a set of assumptions about product technology into a product available for sale". During the development process, information and material, as well as energy are converted (Schlick, Kausch and Tackenberg, 2008, p. 95).

Demand's diversity regarding a certain product is important for product development. For product's success, it is important that the product fulfills all customer's requirements so that they are willing to buy it. For company's success, it is important that the sales market for the offered goods is adequate and the service provision is economical. This concerns all fields along the value chain, such as product development, production, assembly, procurement, logistics etc. (Ponn and Lindemann, 2008, p. 273). Furthermore, 80% of product's costs are defined during the product development process (Bayer, 2010, p. 89). Therefore, an exact definition of market's and customer's demands regarding the product is essential (Kairies, 2006, p. 104). Product development time is also a major factor for company's success, because development's quality and costs are related to time (Murmann, 1994, p. 237). The development costs comprise all expenditures regarding the development project. These include for example the required resources and working materials (Dellanoi, 2006, p. 56). Product development's costs are influenced by the variety of the different development tasks and the required resources (Zich, 1996, p. 10). Development costs gain more and more importance, because the increase of variants in the product portfolio results in a reduction of the sold amount per developed product variant (Dellanoi, 2006, p. 56). Ragatz, Handfield and Petersen (2002, p. 390) identify in their research that in literature, product development is described as a core process for the new global economy's success. In the last years, the development time of industrial goods has been strongly reduced. Reasons for this trend are customer's behavior change, hardly predictable market fluctuations and increasing globalization. As a consequence of this, product development processes have to adjust to the changed boundary conditions often and quickly (Krause, Franke and Gausemeier, 2007, p. 89).

Modern products are often complex products, because they consist of "thousands of parts and take hundreds of manufacturing and assembly steps to be produced". Most complex products comprise mechanical and electrical components, as well as software, control modules and human-machine interfaces (ElMaraghy *et al.*, 2012, p. 793). Thus, it is important to develop products, which can be derived from other products (Krumm, Schopf and Rennekamp, 2014, p. 195).

Complexity in product development is influenced by several internal and external sources (Dehnen, 2004, pp. 33-34; Ophey, 2005, p. 19), called complexity drivers. Puhl (1999, p. 31) and Perona and Miragliotta (2004, p. 104) describe complexity drivers as factors or indicators, which influence a system's complexity. Internal sources comprise products, processes and technologies. The market with its trends, competitors, customer requirements and restrictions by law are external sources (Ophey, 2005, p.19). According to Wildemann (2012, p. 202), complexity in product development is caused by demand variety, uncertain objectives, dynamics, high time pressure and restricted resources.

Product development's complexity has mainly increased in 2 aspects: Product complexity and process complexity (Tomiyama and D'Amelio, 2007, p. 473). Product complexity is characterized by its product design, the number of parts, elements or materials and their interdependencies, as well as the dynamics of product's introduction or change (Edersheim and Wilson, 1992, pp. 27-33; Kirchhof, 2003, p. 40). For product's complexity increase, further reasons are the rapid technological development and the fact that products have become "significantly multi-disciplinary or even inter-disciplinary" (Tomiyama and D'Amelio, 2007, p. 473). Process complexity is mainly characterized by the amount of different development tasks and their inter-dependencies (Lenders, 2009, p. 17), the process design and dynamics, as well as the multidimensional target expectation (Edersheim and Wilson, 1992, pp. 28-34; Klabunde, 2003, p. 8; Kirchhof, 2003, p. 40). Process design comprises the number of direct and indirect process steps, their interdependencies, the design of process interfaces, the level of difficulty, as well as the controllability and consistency of each step. Process dynamics refer to the rate, at which processes or product design and operational parameters (e.g. tolerances) are changing

(Edersheim and Wilson, 1992, pp. 28-34; Klabunde, 2003, p. 8; Kirchhof, 2003, p. 40). Furthermore, process complexity describes the multidimensional demand for a structural coordination between different interfaces (Dehnen, 2004, p. 34) and can be attributed to the stakeholders' involvement in the product development process (Tomiyama and D'Amelio, 2007, p. 473). More and more stakeholders are involved during the development process and their roles are often changing. This leads to an increase in process complexity. It is seen that these 2 aspects, product and process complexity, make the development of modern products extremely difficult (Tomiyama and D'Amelio, 2007, p. 473). Another important aspect in product development is product portfolio complexity (Vogel and Lasch, 2015, p. 101). Product portfolio complexity is determined by the product range or the variant range, the number of their elements and the dynamics of product portfolio's variability (Kirchhof, 2003, p. 40; Lübke, 2007, p. 173; Schoeller, 2009, p. 50). In literature, the previously mentioned 3 aspects are also described as categories. The 3 complexity drivers 'product complexity', 'process complexity' and 'product portfolio complexity' are derived from these categories (Vogel and Lasch, 2015, p. 101). As a result of this, managing and controlling product development's complexity requires an understanding of the types and sources of complexity, as well as the development of methodologies and metrics for sustainable competitiveness (ElMaraghy *et al.*, 2012, p. 798). Thus, a detailed complexity analysis in these 3 categories is necessary (Dehnen, 2004, p. 9). Keuper (2004, p. 82) describes that handling a company's complexity depends on its complexity drivers. Thus, complexity drivers play a significant role for complexity management.

The product development process is further characterized by uncertainty, which results from the ambiguity about target's achievement (Lenders, 2009, p. 17). That includes uncertainties in time, resources, market, technology and organization (Thiebes and Plankert, 2014, pp. 167-168). Time uncertainty comprises the ambiguous target achievement at the planned date (Lenders, 2009, p. 17). Resource uncertainty concerns the amount's ambiguity of the required financial and personnel resources at project's beginning. Market uncertainty results from the insufficient information about market's requirements and conditions (Thiebes and Plankert, 2014, p. 167), as well as the changing of customer's requirements over time (Thiebes and Plankert, 2014, pp. 167-168; Dehnen, 2004, pp. 37-38). Technological uncertainty refers to an inadequate knowledge about science and technology (Thiebes and Plankert, 2014, p. 168; Herstatt, Buse and Napp, 2007, p. 11). Organizational uncertainty is determined for example by the manager of a project team or company's higher management (Steinhoff, 2006, pp. 38-39).

In principle, the product development process is structured in different phases. Each phase is based on the results of the previous development phase (Bick and Drexl-Wittbecker, 2008, p. 69). Krause, Franke and Gausemeier (2007, p. 89) define a process as sequence of operations, which interact and convert inputs to results by the use of resources. Product development process is often the longest part of bringing a product to market (Govil and Proth, 2002, p. 103). Dehnen (2004, p. 23) describes in his PhD-thesis 3 phases, which are often arranged sequentially: Planning phase, concept phase, as well as product and process realization phase. Davila (2000, p. 385) extends the description of Dehnen and describes in his publication 5 phases, which are also arranged sequentially: Planning phase, concept phase, product design, testing and production start-up. In this chapter, the description of Dehnen (2004, p. 23) and Davila (2000, p. 385) are combined in a 5-phases-model, consisting of planning phase, concept phase, product and process realization phase, testing and production start-up (see Figure 30).

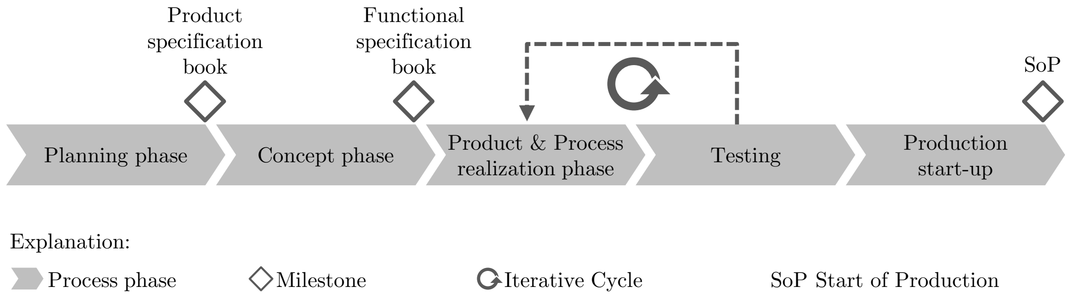


Figure 30: Phases of the product development process according to Dehnen and Davila

The content and objectives of the different phases are described as follows:

- **Planning phase**

  Product development's starting point is the product idea, initialized by internal or external information (Dehnen, 2004, p. 23). The objective of the first phase is to concretize the requirements and the course of the development project (Davila, 2000, p. 385; Dehnen, 2004, p. 24; Lenders, 2009, pp. 11-12). During the planning phase, the organization defines the product characteristics and the target markets based on customer requirements, economic market changes, technological trends and the competitors (Davila, 2000, p. 385; Dehnen, 2004, p. 24). Based on these, the product portfolio is specified (Albers and Gausemeier, 2012, pp. 18-19). Product portfolio consists of all products, which are offered on the market by the company (Ponn and Lindemann, 2008, p. 399) and is classified in product's range diversity and depth (Renner, 2007, p. 12). The diversity of product's range is described by the amount of different product types (e.g. cars, trucks). Product's range depth comprises the amount of different product variants (e.g. limousine, roadster, SUV) (Renner, 2007, p. 12). Furthermore, within the planning phase, the availability of the required personnel, technical and financial resources are checked, because they are the basis for development project's successful completion (Ulrich and Eppinger, 2000, p. 16). At the end of the planning phase, the qualitative targets regarding product's characteristics, milestones, etc. are transferred to the product specification book (Dehnen, 2004, p. 24).

- **Concept phase**

  In the second phase, the requirements of the product specification book are concretized more in detail (Davila, 2000, p. 385; Dehnen, 2004, p. 24), for example, target costs, technological performance, customer interfaces, market release dates and organizational resources (Davila, 2000, p. 385). The objective of the second phase is to define product's concept based on the product architecture. The product architecture represents the implementation of the planned product functions into a tangible physical structure (Dehnen, 2004, p. 24). During the concept phase, different product architectures are defined based on the product specification book (Dehnen, 2004, pp. 24-25; Thiebes and Plankert, 2014, p. 167). However, the product architecture, which fulfills all requirements is the basis for product's concept. At the end of the concept phase, the specific targets regarding costs, time and quality are transferred to the functional specification book (Dehnen, 2004, p. 25).

- **Product and process realization phase**

  In the third phase, the physical products and processes are developed (Dehnen, 2004, p. 25; Davila, 2000, p. 385). The objective is to realize the presettings of the functional specification book (Dehnen, 2004, p. 25). During the third phase, the particular parts, components and modules are developed and the corresponding processes for production and procurement are determined based on the functional specification book (Dehnen, 2004, p. 26).

- **Testing**

  During the fourth phase, the developed parts, components and modules, as well as the corresponding processes are tested and compared with the functional specification book (Dehnen, 2004, p. 26). The objective is to confirm that the product fulfills all requirements and is prepared for its release (Davila, 2000, p. 385). If the presettings of the functional specification book are not fulfilled, the product and process realization phase is passed through again (Dehnen, 2004, p. 26) and the product specifications or the product concept are reevaluated (Davila, 2000, p. 385). Therefore, the development process is an iterative process and not a linear process as previously explained (Davila, 2000, p. 385; Dehnen, 2004, p. 25).

- **Production start-up**

  In the last phase, the test and pilot series are used to check, in what way the time, quality and cost targets can be realized for serial production. Potential failures and disturbances have to be identified and eliminated. Subsequently, the product release and the start of production (SoP) occur (Dehnen, 2004, p. 26).

The complexity management approach for resource planning in variant-rich product development, which is presented in section 7.3, is focused on the first phase in product development, the planning phase. According to literature, within the planning phase, the product portfolio is specified (Albers and Gausemeier, 2012, pp. 18-19) and the availability of the required personnel, technical and financial resources are checked (Ulrich and Eppinger, 2000, p. 16). The required resources in product development are directly related to the variety in product and process (Franke and Firchau, 2001, p. 9; Bohne, 1998, p. 33) and complexity (Bohne, 1998, pp. 9-10). Product variety causes an increased product development effort, because variety is often built at the beginning of the value chain (Bick and Drexl-Wittbecker, 2008, p. 15). Zich (1996, p. 11) argues that the adaption of existing product variants to create new variants is associated with an additional use of resources. Process variety has also an impact on the required resources within a project (Bohne, 1998, p. 33). Product's and process' variety are complexity drivers, which have to be managed. According to Collinson and Jay (2012, p. 33), complexity wastes resources, because things are done, which are not value adding. Thus, an approach, which combines resource planning and complexity management is required in the planning phase to avoid a waste of resources. With the resource planning, the required resources can be evaluated at an early stage within a development project.

7.2.3 Resource planning

Resource planning comprises the quantitative planning of human, material and financial resources over time within a project (Berner, Kochendörfer and Schach, 2013, p. 219). Resources are required for the development of new products (Wleklinski, 2001, p. 27). The employees within a development project use resources for their development work (Schlick, Kausch and Tackenberg, 2008, p. 95), which have to be procured. Procurement's objective is to provide all required objects for the company, which are not produced by itself (Arnold, 1997, p. 3). The procurement of resources, equipment and working materials is material management's objective (Harlander and Platz, 1991, p. 16). The success of a development project is connected with the amount of available resources. In successful development projects, the required resources are available in a higher proportion than in less successful projects (Wleklinski, 2001, p. 27). However, the qualitative and quantitative amount of the resources is restricted (Zich, 1996, p. 10). Thus, resources play a significant role for product development's effort and have to be applied efficiently (Wleklinski, 2001, p. 27). In the case of resource's shortage, company's departments have to use the available resources together. Thereby, it is necessary to find an optimum way for resources' division (Adam, 1998, pp. 37-38).

The term "resource" describes everything that is available in the company and directly or indirectly accessible (Müller-Stewens and Lechner, 2003, p. 357). In literature, resources are classified in several different ways. Resources are often differentiated in tangible and intangible resources. Tangible resources are physical available resources within the company, for example equipment, facilities, machineries or capital assets. In contrast, intangible resources are not physically available, these include know-how, intelligence, brands, image or patents (Stirzel, 2010, p. 119). Further, Stirzel (2010, p. 119) classifies resources according to their origin in internal and external resources, regarding their character in material and immaterial resources and regarding their type in financial, physical, human and technological resources. Bullinger, Fähnrich and Meiren (2003, p. 278) divide resources in material, immaterial and human resources. Dehnen (2004, pp. 84-85) follows the definition of Bullinger, Fähnrich and Meiren (2003) and divides the resources also in material, immaterial and human resources. For example, material resources are capital assets, machineries, capacities of rooms or laboratories or information and communication systems. Immaterial resources are patents, brands, contracts or sales channels. Company's employees, such as engineers or managers belong to human resources. Schönsleben (2011, p. 414) introduces a further division and divides resources in consumable (e.g. energy, raw material, tools) and producible resources (e.g. products, final goods). According to Wleklinski (2001, p. 27), resources can be separated in temporal, financial and technical resources. An overview about the characteristics and origins of the different types of resources is shown in Figure 31.

Resources	Resource's characteristics				
	Tangible (material)			Intangible (immaterial)	Human
	Physical	Technological	Financial		
Resource's origin: [1] Internal ([3] Consumable, [4] Producible); [2] External ([3] Consumable, [4] Producible)	▪ Equipment [1, 2, 3] ▪ Tools [1, 2, 3] ▪ Raw materials [1, 2, 3] ▪ Facilities [1, 3] ▪ Capacities of rooms or laboratories [1, 3] ▪ Energy [1, 2, 3] ▪ ...	▪ Machineries [1, 2, 3] ▪ Information and communication systems [1, 2, 3] ▪ Products [1, 2, 4] ▪ Final goods [1, 2, 4] ▪ ...	▪ Capital assets [1, 2, 3] ▪ ...	▪ Know-how [1] ▪ Intelligence [1] ▪ Brands [1] ▪ Image [1] ▪ Patents [1] ▪ Contrats [1] ▪ Sales channels [1] ▪ ...	▪ Technicians [1, 2, 3] ▪ Engineers [1, 2, 3] ▪ Managers [1, 2, 3] ▪ ...

Figure 31: Overview about resource's characteristics and origins

As already mentioned, complexity, variety and the use of resources are closely connected. The complexity level has a high influence on the amount of required resources (Bohne, 1998, pp. 9-10). Collinson and Jay (2012, p. 33) argue that complexity wastes resources, because things are done, which are not value adding. Thus, a complexity management approach is necessary to avoid the waste of resources.

7.2.4 Research methodology and results

This chapter's purpose is to develop a praxis-oriented complexity management approach for resource planning in variant-rich product development. In product development, the amount of required resources is closely connected to the amount of different product variants (Franke and Firchau, 2001, p. 9) and their complexity (Bohne, 1998, pp. 9-10). Resource planning comprises the quantitative planning of human and material resources over time.

In the first step before developing a new complexity management approach for resource planning, the existing literature must be identified, analyzed and evaluated. Furthermore, an overview of existing complexity management approaches and their applicability for resource planning has to be described. In the second step, the approach is developed based on literature's findings.

For the literature review and the development of a new praxis-oriented complexity management approach, the following 4 research questions were determined:

- RQ 1: What different approaches for complexity management currently exist in scientific literature?
- RQ 2: What focus and structure do the existing approaches have?
- RQ 3: What approaches contain information about resource planning and are applicable for practice?
- RQ 4: What different stages are necessary for a praxis-oriented complexity management approach for resource planning in variant-rich product development?

Before conducting a literature research, it is necessary to define the right search terms and databases. The search terms are based on the words that frame the research questions. Further, the researcher must use a "particular grammar and logic" to conduct a search that will acquire the appropriate publications (Fink, 2014, p. 3). In literature, the terms "approach", "model", "method", "concept", "procedure" and "framework" are often used synonymously for describing a complexity management approach. Thus, all these terms were used in a combination for this literature research. One possibility is to combine the key words and other terms with Boolean operators, such as AND, OR and NOT. Further, the operator NEAR can be used to identify literature, where the keywords have a close connection to each other. The application of Boolean operators depends on the specific database. The research was performed in English and German to extend the results and to prevent the elimination of important articles. The following 8 databases, specialized in science and economics, were used for the literature research: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink. For this research, the time period was restricted between 1900/01/01 and 2015/12/31.

Table 34 shows the framework of the literature collections including the applied databases, search terms, searching dates and the total number of results. The search resulted in 16,130 literature sources including research papers from journals, conference proceedings, books, essays and PhD theses.

However, several literature sources are found repeatedly. Furthermore, literature research and analysis always accumulate many publications, but only a few are relevant. Thus, it is necessary to screen and synthesize the results to identify the relevant literature sources (Fink, 2014, p. 5).

Table 34: Framework of literature collection

Database	Search terms	Date	Results
EBSCOhost	'complexity' N3 (approach OR model OR method OR concept OR procedure OR framework)	2016/07/02	768
	'Komplexität*' N3 (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/07/02	126
Emerald	"complexity" AND [approach OR model OR method OR concept OR procedure OR framework]	2016/07/10	156
	"Komplexität?" AND [Ansatz OR Modell OR Method? OR Konzept OR Vorgehensweise OR Rahmen?]	2016/07/10	16
GENIO/WISO	complexity ndj2 (approach OR model OR method OR concept OR procedure OR framework)	2016/07/12	696
	Komplexität* ndj2 (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/07/14	796
Google Scholar	"complexity" AND ("approach" OR "model" OR "method" OR "concept" OR "procedure" OR "framework")	2016/07/16	3,122
	"Komplexität*" AND ("Ansatz" OR "Modell" OR "Method*" OR "Konzept" OR "Vorgehensweise" OR "Rahmen*")	2016/07/26	524
IEEE Xplore	complexity NEAR/2 (approach OR model OR method OR concept OR procedure OR framework)	2016/07/28	4,555
	Komplexität* NEAR/2 (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/08/05	0
JSTOR	complexity AND (approach OR model OR method OR concept OR procedure OR framework)	2016/08/05	524
	Komplexität* AND (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/08/05	233
ScienceDirect	complexity W/3 (approach OR model OR method OR concept OR procedure OR framework)	2016/08/07	3,435
	Komplexität* W/3 (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/08/12	0
SpringerLink	complexity NEAR/2 (approach OR model OR method OR concept OR procedure OR framework)	2016/08/15	675
	Komplexität* NEAR/2 (Ansatz OR Modell OR Method* OR Konzept OR Vorgehensweise OR Rahmen*)	2016/08/15	504
		Total:	**16,130**

The researched literature was synthesized based on the qualitative content analysis and the aforementioned research questions. According to Gläser and Laudel (2010, pp. 197-199), the content analysis is used to analyze literature and to identify the occurrences of specified information systematically. Within the qualitative content analysis, the information is extracted, formatted and evaluated to answer the research questions.

The synthesizing process resulted in 48 approaches in the time period between 1992 and 2015 (see Table 35). As a result, 56% of the existing approaches are focused on general in manufacturing companies. The remaining 44% are separated in other fields, such as product development (8%), procurement (2%), production (10%), logistics (4%), internal supply chain (16%) and distribution (4%). In total, 2 approaches are focused on 2 fields. Only 4 approaches are focused on product development.

In the next step, the identified approaches are analyzed and described according to their structure and targets (see Table 35). Furthermore, the existing approaches are evaluated based on the applicability for resource planning. This includes complexity management's objectives (e.g. complexity analysis and evaluation), product development's characteristics (product, process and product portfolio) and objectives, as well as the principle of resource planning (quantitative planning of resources over time) and their applicability in product development. For the evaluation, the following 3 criteria are determined:

- Fulfilled (+ +): Content and precise methods are described
- Partial fulfilled (+): Content is described without precise methods
- Not fulfilled (-): Content and methods are not described

In the first step, the identified approaches are analyzed according to their structure and targets to identify commonalities and differences. Generally, 7 stages of complexity management can be identified and were applied in literature: Complexity analysis (N: 37; 77%), complexity evaluation (N: 20; 42%), determination of complexity strategies (N: 39; 81%), determination of appropriate complexity instruments (N: 11; 23%), complexity planning (N: 7; 15%), complexity management's implementation (N: 10; 21%) and complexity controlling (N: 12; 25%). The most applied stages are determination of complexity strategies, complexity analysis and evaluation. Thus, these stages are very important for a complexity management approach. In literature, 1 approach is identified, which consists of all stages.

Table 35: Overview about existing approaches for complexity management and resource planning (Part A)

Explanation for focus:
G General in manufacturing companies
PD Product development
PC Procurement
PR Production
L Logistics
SC Internal supply chain
D Distribution

Explanation for target and applicability for resource planning:
+ + fulfilled
+ partially fulfilled
- not fulfilled

Author(s)	**Focus**	**Approach's structure**							**Target**			**Applicability for resource planning**
		Complexity analysis	Complexity evaluation	Determine complexity strategy	Determine complexity instruments	Complexity planning	Implement complexity management	Complexity controlling	Product complexity	Process complexity	Product portfolio complexity	
Grossmann (1992, pp. 209-213)	G	•			•		•		-	-	-	-
Wildemann (1995, pp. 23-24)	PR			•	•				-	-	-	-
Fricker (1996, pp. 112-114)	G	•	•						-	-	-	-
Warnecke and Puhl (1997, pp. 360-362)	G	•	•	•					-	+	-	-
Bliss (1998, pp. 151-164)	G			•					+ +	-	-	-
Bohne (1998, pp. 91-92)	G	•	•	•				•	-	-	-	-
Rosemann (1998, pp. 60-62)	G			•					-	-	-	-
Puhl (1999, pp. 45-97)	G	•				•		•	-	+	-	-
Wildemann (1999a, pp. 66-67)	PC			•					-	-	-	-
Bliss (2000, pp. 194-208)	G			•					+ +	-	-	-
Westphal (2000, p. 28)	L			•					-	-	-	-
Miragliotta, Perona and Portioli-Staudacher (2002, pp. 382-383, 388-392)	G	•	•	•	•				-	-	-	-
Kim and Wilemon (2003, pp. 24-27)	PD		•	•			•		-	-	-	-
Kirchhof (2003, pp. 167-243)	G	•				•			-	-	-	-
Dehnen (2004, pp. 49-61)	PD			•					+ +	+ +	+ +	-
Hanenkamp (2004, pp. 59-138)	PR			•		•	•	•	+	+	-	-
Meier and Hanenkamp (2004, pp. 118-127)	SC	•		•	•				-	-	-	-
Perona and Miragliotta (2004, pp. 112-114)	PR, L	•		•					-	-	-	-
Blecker, Kersten and Meyer (2005, pp. 51-52)	G	•	•						-	-	-	-
Geimer (2005, pp. 45-46)	SC	•		•			•		-	-	-	-
Geimer and Schulze (2005, p. 102)	SC	•		•			•	•	-	-	-	-
Anderson *et al.* (2006, p. 21)	G	•	•	•					-	-	-	-
Greitemeyer and Ulrich (2006, p. 8)	G	•		•		•		•	+	+	-	-
Denk (2007, pp. 20-21)	G	•		•					-	-	-	-

Table 35: Overview about existing approaches for complexity management and resource planning (Part B)

Explanation for focus:
G General in manufacturing companies
PD Product development
PC Procurement
PR Production
L Logistics
SC Internal supply chain
D Distribution

Explanation for target and applicability for resource planning:
+ + fulfilled
+ partially fulfilled
- not fulfilled

		Approach's structure							Target			
Author(s)	**Focus**	Complexity analysis	Complexity evaluation	Determine complexity strategy	Determine complexity instruments	Complexity planning	Implement complexity management	Complexity controlling	Product complexity	Process complexity	Product portfolio complexity	**Applicability for resource planning**
Marti (2007, pp. 152-153)	G		•	•					+ +	-	-	-
Meyer (2007, pp. 129-142)	D	•		•				•	-	-	-	-
Bick and Drexl-Wittbecker (2008, pp. 78-81)	G			•					+ +	+ +	-	-
Schuh *et al.* (2008, pp. 447-448)	G	•							+ +	-	-	-
Denk and Pfneissl (2009, pp. 28-32)	G	•		•					-	-	-	-
Lasch and Gießmann (2009b, pp. 114-118)	G	•	•	•		•	•	•	+	+	+	-
Lindemann, Maurer and Braun (2009, pp. 61-66)	PD	•		•					+	-	-	-
Blockus (2010, pp. 269-293)	G	•		•		•		•	-	-	-	-
Warnecke (2010, p. 641)	G	•	•	•					-	-	-	-
Isik (2011, pp. 422-423)	SC	•	•	•				•	-	-	-	-
Kersten (2011, pp. 15-18)	SC	•	•	•					-	-	-	-
Schawel and Billing (2011, pp. 110-111)	G	•		•					-	-	-	-
Fabig and Haasper (2012, pp. 17-19)	G	•		•	•		•		+	-	+	-
Koch (2012, p. 54)	G	•	•	•					-	-	-	-
Lammers (2012, pp. 85-135)	D	•	•		•				-	-	-	-
Aelker, Bauernhansl and Ehm (2013, pp. 81-82)	SC	•	•	•					-	-	-	-
Boyksen and Kotlik (2013, pp. 49-52)	G	•		•					-	-	-	-
Jäger *et al.* (2013, pp. 342-343)	PR, SC	•	•	•	•				-	-	-	-
Meier and Bojarski (2013, pp. 548-551)	G	•	•						+ +	+ +	-	-
Serdarasan (2013, pp. 537-538)	SC	•	•	•	•				-	-	-	-
Grimm, Schuller and Wilhelmer (2014, pp. 95-97)	G	•		•	•		•	•	-	-	-	-
Schöttl *et al.* (2014, pp. 258-259)	PR	•	•		•				-	+	-	-
Wassmus (2014, pp. 61-65)	G	•		•			•	•	+ +	-	-	-
Vogel and Lasch (2015, pp. 109-130)	PD	•	•	•	•	•	•	•	+ +	+ +	+ +	+ +

As already mentioned in subsection 7.2.2, complexity in product development is characterized by product complexity, process complexity and product portfolio complexity. Furthermore, the amount of required resources within a product development project is directly related to its complexity. Based on this, the existing approaches are analyzed according to these 3 target categories. Most of the identified approaches have no explicit target or focus. Only 2 approaches are focused on all mentioned complexity categories.

In the next step, the identified approaches are evaluated according to their applicability for resource planning. As a result, there is only 1 approach, which fulfills the requirements in total. Furthermore, this approach is focused on product development and thus practicable for the following case study. However, the complexity management approach from Vogel and Lasch (2015, pp. 109-130) comprises a broader field. Furthermore, the order of the different stages is not feasible in practice.

In principle, the approach from Vogel and Lasch with the 4 stages complexity analysis (stage 1), complexity evaluation (stage 2), application of complexity strategies (stage 3) and complexity planning and controlling (stage 4) can be applied in this case study. However, during the practical application, it was seen that in practice, the users (e.g. managers) want to have a first implication about the calculated total amount of required resources before they apply a certain complexity strategy. Furthermore, the practitioners want to compare the amount of calculated resources first with project's objectives, as well as the amount of available resources before complexity strategy's application. In the case that the calculated amount of resources is not conform to project's objectives or exceeds the total amount of available resources, the practitioners apply different complexity strategies to adjust the calculated amount of required resources.

Therefore, a new and structurally optimized approach based on Vogel and Lasch's findings, especially for the field resource planning is developed and presented in this chapter to increase the practicability in practice. With the new complexity management approach, the research gap is closed.

7.3 Resource planning in variant-rich product development

7.3.1 Structure of the new approach

As a result of the literature research, only 1 complexity management approach was identified, which fulfills all requirements and is applicable for resource planning in product development. Vogel and Lasch (2015, pp. 109-130) developed a 4-stage complexity management approach for variant-rich product development based on the existing literature and the risk management strategy. The stages are complexity analysis, complexity evaluation, application of complexity strategies, as well as complexity planning and controlling. It is structured as a recurring cycle with a modular structure. The approach is focused on product development's 3 main dimensions 'product complexity', 'process complexity' and 'product portfolio complexity'. Furthermore, Vogel and Lasch describe different methods and tools for complexity management to gain practicability. However, the complexity management approach from Vogel and Lasch (2015, pp. 109-130) comprises a broader field. Therefore, a new approach based on their findings, especially for the field resource planning is developed and applied on a recent development project in the automotive industry to verify the scientific results. The new developed complexity management approach for resource planning in variant-rich product development comprises also 4 stages and is described in Figure 32.

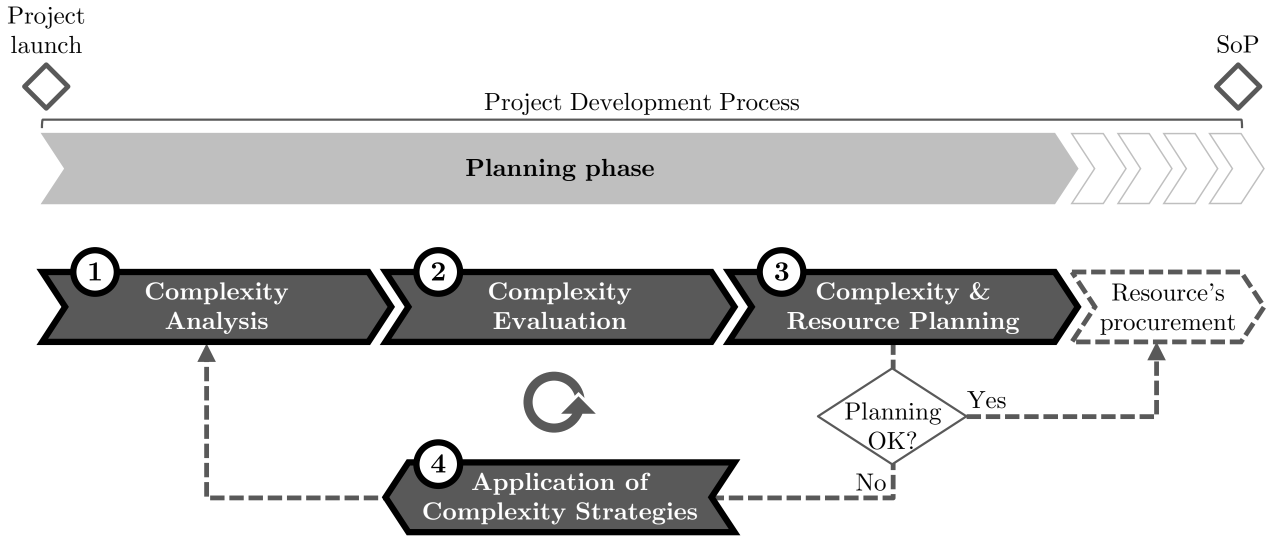


Figure 32: Structure of the complexity management approach for resource planning

As already mentioned, the new approach is applied on a recent development project in the automotive industry. Cars are the most complex mass-produced products on the market, because they combine many different parts, components, technologies and functions (Moisdon and Weil, 1996, cited in Aggeri and Segrestin, 2007, p. 38). Thus, car's development can be classified as complex (Piller and Waringer, 1999, p. 18). The development process takes between 3 to 4 years and involves hundreds of engineers, technicians and partners (Moisdon and Weil, 1996, cited in Aggeri and Segrestin, 2007, p. 38). Furthermore, several resources are required for the development of complex products, such as cars. Before starting a development project, a first indication of the required resources has to be calculated.

The following case study is focused on a powertrain development project of a hybrid car, especially its software application. The powertrain comprises all components within a vehicle that are needed to change the chemical energy to mechanical energy and to provide the necessary operating power to negotiate the driving resistances (Braess and Seiffert, 2013, p. 336). The powertrain of a car belongs to the mechatronical products and is characterized through mechanical, electrical and software elements (Feldhusen and Gebhardt, 2008, p. 44), which interact functionally (Dolezal, 2008, p. 52). The mechanical components are the engine (e.g. combustion engine, electric motor, hybrid propulsion), the starting element (e.g. clutch), the transmission (e.g. automatic transmission or manual transmission) and the final drive (power take-off unit and axle drive) (Trzesniowski, 2014, p. 678). The control units belong to the electrical elements and are characterized through the software. The mechanical elements are controlled through the electrical elements and their software.

The electronical components can only fulfill their capability when they are perfectly adjusted to the given type of vehicle. The software functions contain a vast number of different and changeable parameters. The adaption of these parameters to the given vehicle variant (e.g. all wheel drive or rear wheel drive) or the market variant (e.g. Europe or United States of America or China), as well as the adaption to each operating condition (e.g. cold run, extreme heat or heights), is called application (Reif, 2011, p. 226). The adaption of existing product variants to create new variants is associated with an additional use of resources (Zich, 1996, p. 11).

7.3.2 Stage 1 – Complexity analysis

Complexity in a project, especially in product development, requires a detailed complexity analysis to increase transparency about complexity's dimension, weighting and relevance. The analysis results are the basis for project planning and should be presented in the form of criteria and parameters (Warnecke, 2010, p. 640).

The complexity analysis stage is subdivided in 3 steps:

- Complexity problem's analysis
- Complexity driver's identification and analysis
- Product portfolio's analysis

The first step is to identify and formulate the tangible problem. This is the basis for the demand for action (Grossmann, 1992, p. 209; Fricker, 1996, p. 113; Schöttl *et al.*, 2014, p. 258). According to Hauschildt (1977, p. 127), problem's complexity is related to a problem's structure, its parts and uncertainty. For analyzing the complexity problem, individual questionnaires are used in literature (Schöttl *et al.*, 2014, p. 258). In this case study, the investigated object is the powertrain of a hybrid car. Expert interviews and questionnaires are used in this research to identify the complexity problem in the powertrain product development department. Thereby, product development's higher management, as well as the personnel were involved in this research process. The result was that the powertrain product portfolio increased continuously in the last years to gain market shares and to be competitive. Furthermore, the legal requirements for environmentally friendly products have also increased. However, the available development budget and time for projects are decreasing successively. In addition, the product variants are characterized by different complexity levels. Thus, the management is faced to develop an increased powertrain product portfolio in less time with the same or less input and resources. According to Nurcahya (2009, pp. 59-62), the hybrid powertrain was abstracted to a product model (see Figure 33). The product model is an abstraction of a real product and contains all relevant elements or modules for product's characterization (Nurcahya, 2009, pp. 54-61). This is the basis for a detailed problem and complexity analysis, including complexity driver's identification, analysis and evaluation. In the case study, the product model of a hybrid powertrain is divided into 6 main modules (1 - engine; 2 - induction system; 3 - fuel injection system; 4 - exhaust system; 5 - hybrid system; 6 - drive train) and contains 49 relevant elements (e.g. turbocharger, injection valve, catalytic converter, electric motor, hybrid battery, power electronics, etc.).

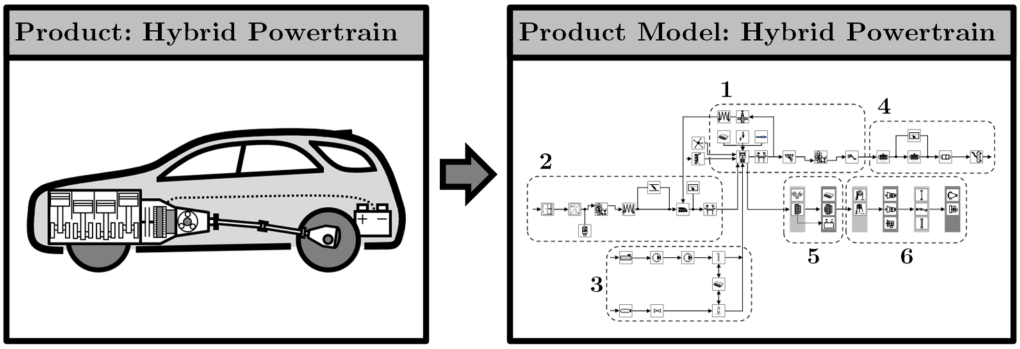


Figure 33: Product model of a hybrid powertrain

Based on the product model, the second step is to identify and analyze the complexity drivers. Complexity driver's analysis and understanding is the basis for developing a clear strategy for complexity management (Serdarasan, 2013, p. 533). Several approaches for complexity driver's identification exist in literature. The most applied approaches are expert interviews, process or systems analysis and influence analysis. The complexity driver represents a certain product component and its variety. In this case study, the complexity drivers in the 3 categories product, process and product portfolio are identified and analyzed by using different approaches, which are applied in a certain order. The result of the previous step is the basis for the next step. Table 36 presents the different approaches in each category, their order and the identified complexity drivers.

Table 36: Applied approaches for complexity driver's identification

Category	Applied approaches for complexity driver's identification and analysis	Identified complexity drivers within hybrid powertrain development
Product	1. Literature analysis 2. Expert interviews 3. Questionnaires 4. Workshops 5. Influence analysis	■ Engine variety ■ Turbocharger ■ Valve controlling ■ Fuel injection system ■ Ignition system ■ Catalytic converter ■ Electric motor ■ High-voltage battery ■ Power electronics ■ Transmission
Process	1. Process analysis 2. Expert interviews 3. Workshops	■ Amount of process steps ■ Amount of conjunctions between different process steps ■ Amount of interfaces to other subsections within the value chain
Product portfolio	1. Expert interviews 2. Workshops 3. Analysis of variant tree	■ Powertrain main attributes: Combustion engine, electric motor, high-voltage battery, transmission, drive train, vehicle type, market, time to market

In the third step, the product portfolio is analyzed in detail to identify product variant's commonalities and differences within the main attributes, which are identified as product portfolio's complexity drivers and characterize a product variant. Variants are products with a high proportion of identical components in the categories geometry, material or technology (Lingnau, 1994, p. 24). DIN 199 (1977 cited in Schwenk-Willi, 2001, pp. 22-23) defines variants as objects with a similar form or function and a high proportion of identical groups or components.

Each product consists of several attributes, which are defined through their characteristics and specifications (Lindemann, 2009, p. 158). They describe a product completely (Bayer, 2010, p. 27). Variant's characteristics describe different features according to function and power. Different characteristics can be clustered in a higher level, if they are correlated to other characteristics (Bayer, 2010, p. 27). According to literature, 2 variants have to differ in minimum 1 attribute (Kesper, 2012, p. 49). In the given example, the V6 petrol engine consists of a cylinder capacity of 3.5 liters. The attribute cylinder capacity of 3.5 liters consists of the characteristic cylinder capacity and its specification 3.5 liters.

According to Nurcahya (2009, pp. 59-68), variant's analysis and the identification of the main attributes are the basis for generating a variant derivation matrix in terms of an effective variant management.

Product portfolio can be divided in reference variants, product variants, product groups and product families. The reference variant is the most complex variant within a product family and the basis for variant's derivation. Product variants are derived from reference variants and clustered within the product family. A product group consists of several product families (Nurcahya, 2009, pp. 52-55). In principle, a product family covers a certain amount of related products (Renner, 2007, p. 12). Furthermore, within a product family, the variants are similar with respect to specified criteria (Nurcahya, 2009, pp. 52-55). In literature, the term "lead variant" is also used synonymously for the term "reference variant". Schuh *et al.* (2007b, pp. 14, 21) describe that the lead-product comprises the maximum requirements of all derivates within a product family and is the basis of a model kit. The characteristics of a lead-product is company individual. In the automotive industry, the lead product [L] can also be a non-real product within a model kit (Schuh *et al.*, 2007b, p. 14). The term "derivate" was established mainly in the manufacturing industry, especially in the automotive industry and describes variants, which are diversified constructively or functionally from the main product (Dellanoi, 2006, p. 47). To gain market shares, companies often develop product derivates based on the lead product (Schuh *et al.*, 2007b, p. 8). Dolezal (2008, p. XI) defines a derivate as a "development of an existing type (of product) for a specialized role". In literature, the term derivate is used synonymously for product variant (Dellanoi, 2006, p. 47). According to their complexity, development effort and time to market, derivates can be further separated in different sizes: e.g. large [DL], medium [DM] and small derivates [DS].

For product portfolio's analysis, all reference and product variants within a product portfolio are compared according to their characteristics to identify commonalities and differences (Nurcahya, 2009, pp. 66-67). According to Nurcahaya (2009), Vogel and Lasch (2015, pp. 113-115) developed a derivation matrix for variant's comparison. The matrix shows, which variants have the same characteristics and can be derived from one another. Basically, the derivation matrix is similar to an influence matrix.

In the powertrain case study, the derivation matrix principle from Vogel and Lasch (2015) was enhanced with expert's cooperation to a derivation table, because the derivation matrix from Vogel and Lasch is only practicable for a small amount of attributes. The derivation table shows, which variants can be derived from the lead variant. In combination with variant's time to market, a hybrid powertrain variant can be described by 7 different attributes (I - combustion engine; II - electric motor; III - high-voltage battery; IV – transmission; V - drive train; VI - vehicle type; VII - market) (see Figure 34). Within the attributes, different product variants with different specifications exist (e.g. in category III: 12 kWh, 10 kWh or 8 kWh lithium-ion high-voltage battery; in category V: All-wheel drive or rear wheel drive; etc.)

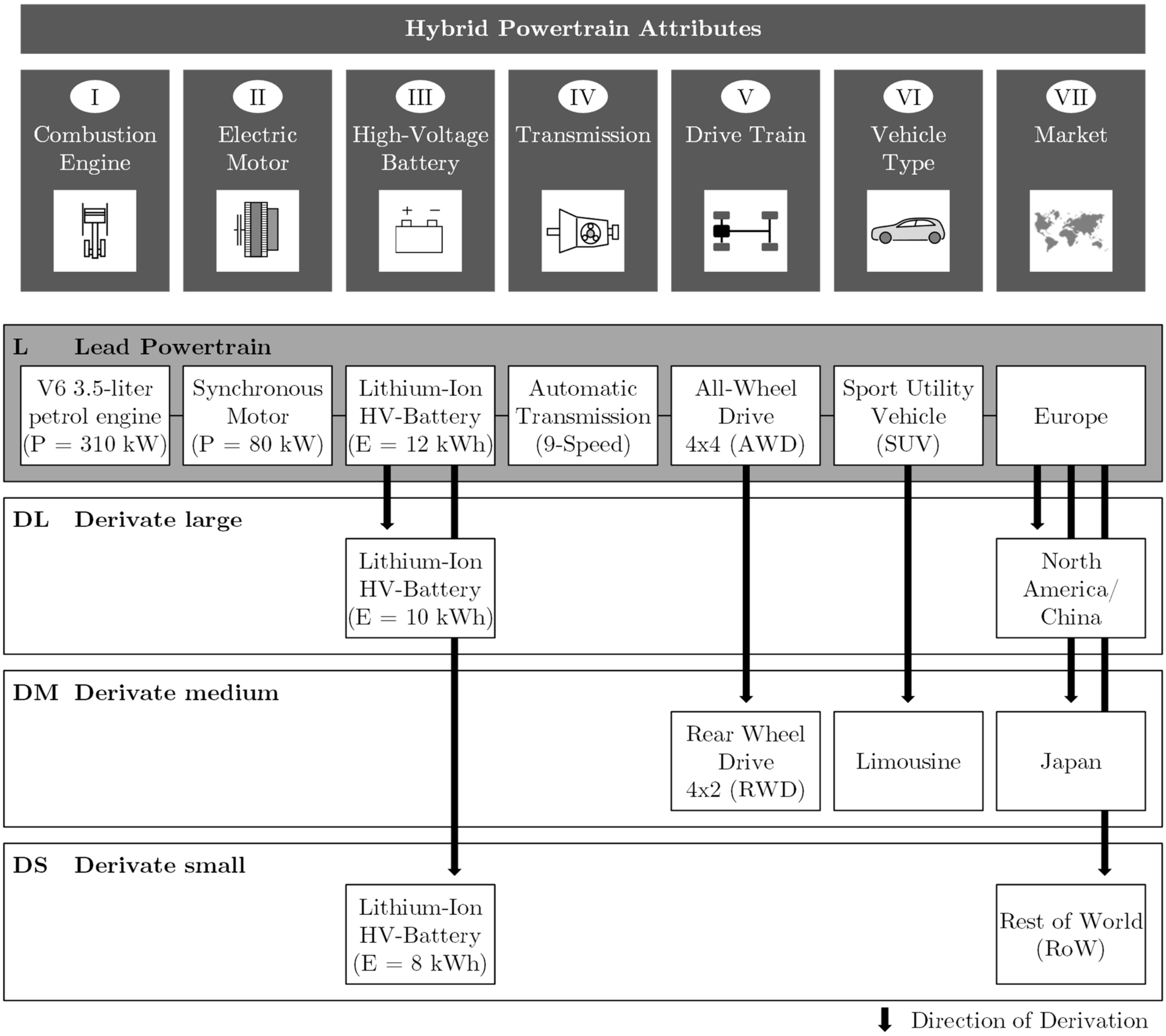


Figure 34: Derivation table for hybrid powertrains

According to product complexity, development effort and time to market, the most complex and expensive product within the product portfolio, which is launched first in the market, is the reference variant, called lead variant. In the case study, the lead variant of the hybrid powertrain portfolio is determined by a V6 3.5 liter engine with a power of 310 kW and a synchronous electric motor with an additional power of 80 kW. Further, the lead powertrain comprises a lithium-ion high-voltage battery with an energy of 12 kWh, a 9-speed automatic transmission and an all-wheel drive and is offered as a sport utility vehicle on the European market.

Product variants, which can be derived from a lead variant are called derivates. As already mentioned, derivates can be further separated in different sizes according to their complexity, development effort and time to market: Large, medium and small derivates. As a result of this classification, a product portfolio can be clustered into 4 different complexity groups: Lead [L]; derivate large [DL]; derivate medium [DM] and derivate small [DS]. The amount of complexity groups is not fix, but user individual and depends on the use case.

The product portfolio in the case study comprises 14 different hybrid powertrain variants (see Table 37). Based on the described attributes, the product portfolio was analyzed and evaluated to identify commonalities and differences. Then, the variants were clustered according to product classification and the developed derivation table into the defined 4 complexity groups.

Table 37: Hybrid product portfolio evaluated according to complexity (N: 14)

	Hybrid Powertrain Attributes								**Complexity Evaluation**	
	Category									
ID	I	II	III	IV	V	VI	VII	Time to market	Δ Difference to lead variant in category...	Result
1	**V6 3.5l**	**80 kW**	**12 kWh**	**Autom.**	**4x4**	**SUV**	**Europe**	**T0**	**- - -**	**L**
2	V6 3.5l	80 kW	12 kWh	Autom.	4x4	**Limous.**	Europe	T1	VI	DM
3	V6 3.5l	80 kW	12 kWh	Autom.	4x4	SUV	**RoW**	T1	VII	DS
4	V6 3.5l	80 kW	12 kWh	Autom.	4x4	**Limous.**	**RoW**	T1	VI, VII	DM
5	V6 3.5l	80 kW	**8 kWh**	Autom.	4x4	SUV	Europe	T1	III	DS
6	V6 3.5l	80 kW	12 kWh	Autom.	4x4	**Limous.**	**Japan**	T4	VI, VII	DM
7	V6 3.5l	80 kW	**10 kWh**	Autom.	4x4	SUV	**China**	T5	III, VII	DL
8	V6 3.5l	80 kW	12 kWh	Autom.	**4x2**	SUV	Europe	T6	V	DM
9	V6 3.5l	80 kW	12 kWh	Autom.	**4x2**	**Limous.**	Europe	T6	V, VI	DM
10	V6 3.5l	80 kW	12 kWh	Autom.	**4x2**	SUV	**RoW**	T7	V, VII	DM
11	V6 3.5l	80 kW	12 kWh	Autom.	**4x2**	**Limous.**	**RoW**	T7	V,VI,VII	DM
12	V6 3.5l	80 kW	**8 kWh**	Autom.	**4x2**	SUV	Europe	T8	III, V	DL
13	V6 3.5l	80 kW	12 kWh	Autom.	4x4	SUV	**N.Amer.**	T9	VII	DL
14	V6 3.5l	80 kW	12 kWh	Autom.	**4x2**	SUV	**N.Amer.**	T10	V, VII	DL

In the example, the reference variant, called lead variant [L], is the powertrain with ID 1. According to the derivation table, the lead variant is the most complex variant and is launched first in the market at the time of T0. All other variants are derivates, because they differ from the lead variant in certain categories (changes are marked black in Table 37) and launched after T0. For variants, which differ in more than one category, the superior category is used for complexity group's clustering.

For example, the variant with ID 2 differs (Δ) in category VI (vehicle type – black marked) compared to the lead variant. In the derivation table (see Figure 34), a change in category VI is classified as a derivate medium [DM]. Thus, the variant is clustered to the complexity group derivate medium. The variant with ID 4 differs in 2 categories: VI and VII. According to the derivation table, the vehicle type limousine is defined as derivate medium. However, the market Rest of World is defined as derivate small. Thus, the superior category is category VI and the variant is clustered in the complexity group derivate medium. The other variants are analyzed and evaluated analogously.

As a result of this analyzing process, 1 lead variant, 4 derivates large, 7 derivates medium and 2 derivates small are identified.

7.3.3 Stage 2 – Complexity evaluation

In the second stage, the complexity in the 3 categories product, process and product portfolio is evaluated. Evaluation's objective in general is to emphasize commonalities and differences between relating object's properties (Kieser and Kubicek, 1983, p. 174).

Complexity management's objective is to achieve a company's optimum complexity degree, where internal and external complexity are equal (Schuh, 2005, p. 43; Boyksen and Kotlik, 2013, p. 49; Reiß, 1993b, pp. 56-57). In product development, internal complexity is characterized by product, process and product portfolio complexity. External complexity is characterized by environmental, demand and competitive complexity (Dehnen, 2004, pp. 33-35). To achieve a company's optimum degree of complexity, internal complexity must be analyzed and evaluated. Vogel and Lasch (2015, pp. 117-122) developed 3 complexity indices on the basis of the systems theory and variety to evaluate product development's internal complexity in the 3 categories product, process and product portfolio. The objective is to compare different development projects in these categories to identify complexity trends over time. The 3 complexity indices Product Complexity Index (PDCI), Process Complexity Index (PRCI) and Product Portfolio Complexity Index (PPCI) are described in Table 38.

In the next step, the 3 complexity indices are applied on the hybrid powertrain development project.

Table 38: Overview about complexity indices, developed by Vogel and Lasch (2015, pp. 116-122)

Complexity Index	Description
Product Complexity Index (PDCI)	The PDCI is based on the product and the difference of variety (*ΔCn*) within the identified product complexity driver's categories. The complexity drivers are weighted (WF_{Cn}) according to development effort, costs and time. The most complex drivers have the weighting factor 1.0. The weighting factors of other drivers are defined in comparison to the most complex driver. The PDCI is formulated as the weighted average of variety difference in all product complexity driver's categories (*Cn*). *N* is the maximum amount of product complexity driver's categories and *n* is the category's number. For PDCI's calculation, an already finished development project is required. In case there is no finished development project, PDCI cannot be calculated. $$\mathrm{PDCI} = \frac{\sum_{n=1}^{N}(\Delta Cn * WF_{Cn})}{N}$$ The PDCI represents the percentage increase or decrease of development effort or costs, in comparison to the basis, e.g. an already finished development project.
Process Complexity Index (PRCI)	The PRCI is developed analogously to the PDCI and based on the development process and the difference of variety within the identified process complexity driver's categories (*ΔPrCn*). The complexity drivers are also weighted according to development effort and time (WF_{PrCn}). For PRCI's calculation, an already finished development project is also required. $$\mathrm{PRCI} = \frac{\sum_{n=1}^{N}(\Delta PrCn * WF_{PrCn})}{N}$$
Product Portfolio Complexity Index (PPCI)	The PPCI is developed based on the results of clustering product variants in the different complexity groups according to their characteristics and the assignment of a certain weighting factor ($WF_{Variant\ n}$) to each variant. The weighting factors are defined according to development effort, costs and time and represent single efforts. The lead variant is the most complex and expensive variant with the highest single effort and has the weighting factor 1.0. Derivate's weighting factors are defined in comparison to the lead variant. The PPCI is calculated by summing up the weighting factors, which are assigned to each variant in the product portfolio. *N* is the total amount of product variants in the product portfolio and *n* is the product variant's number (e.g. ID). PPCI's unit are effort points (*EP*). $$\mathrm{PPCI} = \sum_{n=1}^{N} WF_{Variant\ n}$$ The PPCI facilitates product portfolio's standardization to one measured value under consideration of product and process complexity and provides an overview about complexity in the product portfolio. Furthermore, PPCI describes the total effort, which is dedicated to develop a specific product portfolio within a development project.

7.3.3.1 Product complexity index (PDCI)

For calculating the PDCI, the current hybrid powertrain development project (project #2) is compared with an already completed hybrid powertrain development project (project #1). For comparison, the identified product complexity drivers (see Table 36) are used and divided in 10 complexity driver's categories (C1 to C10):

C1 - engine; C2 - turbocharger; C3 - valve controlling; C4 - fuel injection system; C5 - Ignition system; C6 - catalytic converter; C7 - electric motor; C8 - high-voltage battery; C9 - power electronics and C10 - transmission.

In the first step, the variety in the categories C1 to C10 is identified for project #1 and #2. Next, the differences of variety (Δ Cn) between project #1 and #2 are calculated, using project #1 as the basis. Then, PDCI's percental change is calculated considering different weighting factors (see Table 39). As a result, the new hybrid development project has a complexity increase of 11%, compared to project #1.

Table 39: Calculation of PDCI

PDCI	Product Complexity Driver's Categories *Cn*									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Variety in *Cn* Project #1	1	2	1	1	1	1	1	1	1	1
Variety in *Cn* Project #2	1	1	1	1	1	1	1	3	1	1
$\triangle Cn_{\text{Project\#1→\#2}}$	0%	-50%	0%	0%	0%	0%	0%	+200%	0%	0%
Weighting factor WF_{Cn}	0.8	1.0	1.0	0.6	0.7	0.9	1.0	0.8	1.0	0.6
Result	**PDCI: +11%**									

7.3.3.2 Process complexity index (PRCI)

The PRCI is calculated analogously to the PDCI by comparing the development process of 2 hybrid powertrain projects (project #1 vs. project #2). In this case study, the identified process complexity drivers (see Table 36) are the amount of different process steps (PrC1) and their conjunctions (PrC2), as well as the amount of interfaces to other subsections within the value chain (PrC3). PRCI's calculation is described in Table 40. As a result, the development process of project #2 has a complexity increase of 14% in comparison to project #1.

Table 40: Calculation of PRCI

PRCI	Process Complexity Driver's Categories *PrCn*		
	PrC1	PrC2	PrC3
Variety in *PrCn* Project #1	6	3	5
Variety in *PrCn* Project #2	7	4	5
$\triangle PrCn_{\text{Project\#1→\#2}}$	+17%	+33%	0%
Weighting factor WF_{PrCn}	0.6	1.0	0.7
Result	**PRCI: +14%**		

7.3.3.3 Product portfolio complexity index (PPCI)

For calculating the PPCI, it is necessary to define the weighting factors. Then, the specific weighting factors are assigned to each variant within the complexity groups. The weighting factors are company individual. In the case study, 4 weighting factors for each complexity group are developed according to complexity, development time and effort. The lead variant is the most complex variant in the portfolio and has the highest factor 1.0. Derivates have weaker factors. As already mentioned at the end of subsection 7.3.2, analyzing the product portfolio resulted in 1 lead variant, 4 derivates large, 7 derivates medium and 2 derivates small. PPCI's calculation is described in Table 41. As a result, the PPCI in the case study has a value of 7.9 effort points [EP].

Table 41: Calculation of PPCI

PPCI		Complexity group's amount of product variants	Complexity group's weighting factor	Complexity group's PPCI
Complexity group				
L	Lead	1	1.0	1.0
DL	Derivate large	4	0.75	3.0
DM	Derivate medium	7	0.5	3.5
DS	Derivate small	2	0.2	0.4
			Total PPCI:	7.9 EP

7.3.4 Stage 3 – Complexity and resource planning

Complexity, variety and the use of resources are closely connected (Bohne, 1998, pp. 9-10). Complexity and resource planning are important elements for a target-oriented complexity management (Kirchhof, 2003, pp. 166-167). Company's capacity planning includes planning of resources (Schuh, Millarg and Göransson, 1998, p. 49) and is an important factor for company's competitiveness (Krüger and Homp, 1997, p. 10). Resource planning comprises the quantitative planning of human, material and financial resources over time within a project (Berner, Kochendörfer and Schach, 2013, p. 219). Human resources comprise the total amount of employee's man-years and is therefore a measurement for the expenditure of time. The employees within a development project use resources for their development work (Schlick, Kausch and Tackenberg, 2008, p. 95). Resources can be separated in tangible, intangible and human resources. However, the amount of resources is limited (Zich, 1996, p. 10). Thus, it is necessary to apply the resources efficiently (Wleklinski, 2001, p. 27).

Vogel and Lasch (2015, pp. 128-129) developed a methodology for calculating the precise amount of required resources based on the product portfolio complexity index (PPCI). The PPCI describes the total effort, which is dedicated to develop a specific product portfolio within a development project. Its unit is effort points [EP]. In the first step, a resource factor (RF) for each type of resource (e.g. test vehicles) is determined based on process analysis, expert interviews and evaluation, as well as workshops (e.g. 7 test vehicles per effort point). Furthermore, the resource factors are compared with already completed development projects from the past for verification. The resource factor represents the amount of resources (capacity), which is required for a specific development effort within in a project. With the resource factor, the total development effort [EP] can be translated to a precise amount of required resources. Figure 35 describes the methodology for resources' calculation. The basis is a project's PPCI and the resource factor of each resource type. For resources' calculation, PPCI's value is multiplied with the specific resource factor. The result is a certain amount of resources [N]. This methodology enables a first indication about resources before starting a project.

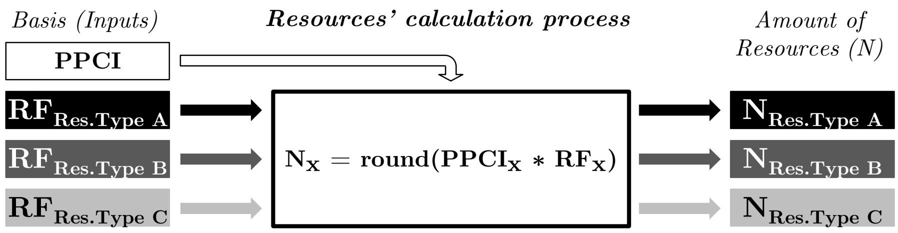


Figure 35: Methodology for resources' calculation based on PPCI and resource factor

In the case study, different types of resources are required for the development and software application of a hybrid powertrain: Human resources (employees) and tangible resources (test vehicles and test rigs). For each type or resource, a specific resource factor was developed ($RF_{Employees}$ = 12 employees per effort point; $RF_{Test\ Vehicles}$ = 9 test vehicles per effort point; $RF_{Test\ Rigs}$ = 9 test rigs per effort point) based on process analysis, expert interviews and workshops. Further, the resource factors were compared with an already finished development project from the past. In the next step, the amount of resources is calculated based on the methodology, described in Figure 35. PPCI's value in the case study is 7.9 effort points (see subsubsection 7.3.3.3). Therefore, the following amount of required resources (capacity) in the hybrid powertrain project is calculated:

- $N_{Employees}$ = PPCI * $RF_{Employees}$ = 7.9 [EP] * 12 [Employees/EP] ≈ 95 Employees
- $N_{Test\ Vehicles}$ = PPCI * $RF_{Test\ Vehicles}$ = 7.9 [EP] * 9 [Test Vehicles/EP] ≈ 71 Test Vehicles
- $N_{Test\ Rigs}$ = PPCI * $RF_{Test\ Rigs}$ = 7.9 [EP] * 9 [Test Rigs/EP] ≈ 71 Test Rigs

After calculating the total amount of required resources, the resources have to be divided over time to enable a sufficient resource planning over time. According to Berner, Kochendörfer and Schach (2013, p. 219), resource planning comprises the quantitative planning of human, material and financial resources over time within a project. In the field of production, all required resources for product's manufacturing are specified in a "resource list" (Schönsleben, 2011, p. 33). This principle can be transferred to product development analogously.

In this case study, all required resources (employees, test vehicles, test rigs) for the development of a hybrid powertrain are also specified in a resource list, called 'resource card' (see Figure 36). After analyzing the product portfolio, the powertrains are classified in different complexity groups according to their complexity level (see subsection 7.3.2 and Table 37). In literature, complexity and its level is associated with the amount of required resources (Bohne, 1998, pp. 9-10). Thus, different resource cards are determined for each complexity level (L – lead; DL – derivate large; DM – derivate medium; DS – derivate small). As already mentioned, each complexity level has an own weighting factor (see subsubsection 7.3.3.3 and Table 41), which is added to the specific resource card and represents a certain development effort. Furthermore, the resource cards contain information about the time period, in which a specific type of resource is needed between development start and time to market according to the development plan. The time period is determined by company's experts and experiences in the past. Based on this, the weighting factor can be divided over a certain time period to calculate an effort index at a certain time (e.g. per month). For example, the weighting of a lead variant is 1.0. The development time is 12 months. The resource employees is also used over a time period of 12 months, whereas the resources test vehicles and test rigs are only used over a period of 9 months. Now, the weighting factor can be separated evenly over a period of 12 months in the case of the employees and over a period of 9 months in the cases of test vehicles and test rigs. As a result, the effort index for the resource type employees is 0.083 effort points per month and the effort index for the test vehicles and test rigs is 0.111 effort points per month. These indices are needed to calculate the total amount of project's development effort during a certain time period. Figure 36 presents 4 different resource cards for the complexity levels lead, derviate large, derivate medium and derivate small. In each card, the weighting factors, the required resources (employees, test vehicles, test rigs) and their application time is presented.

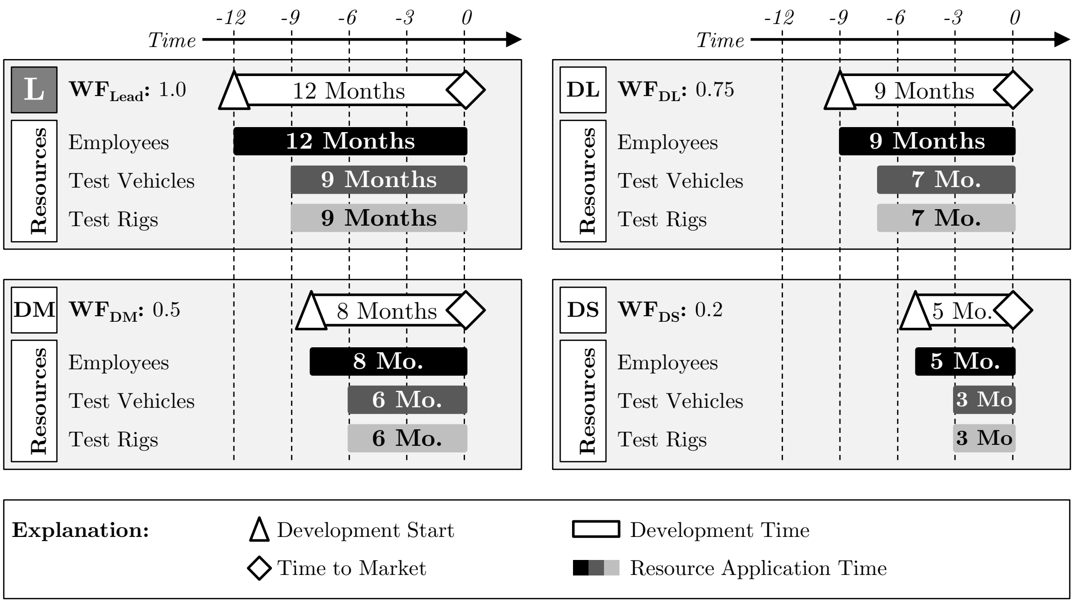


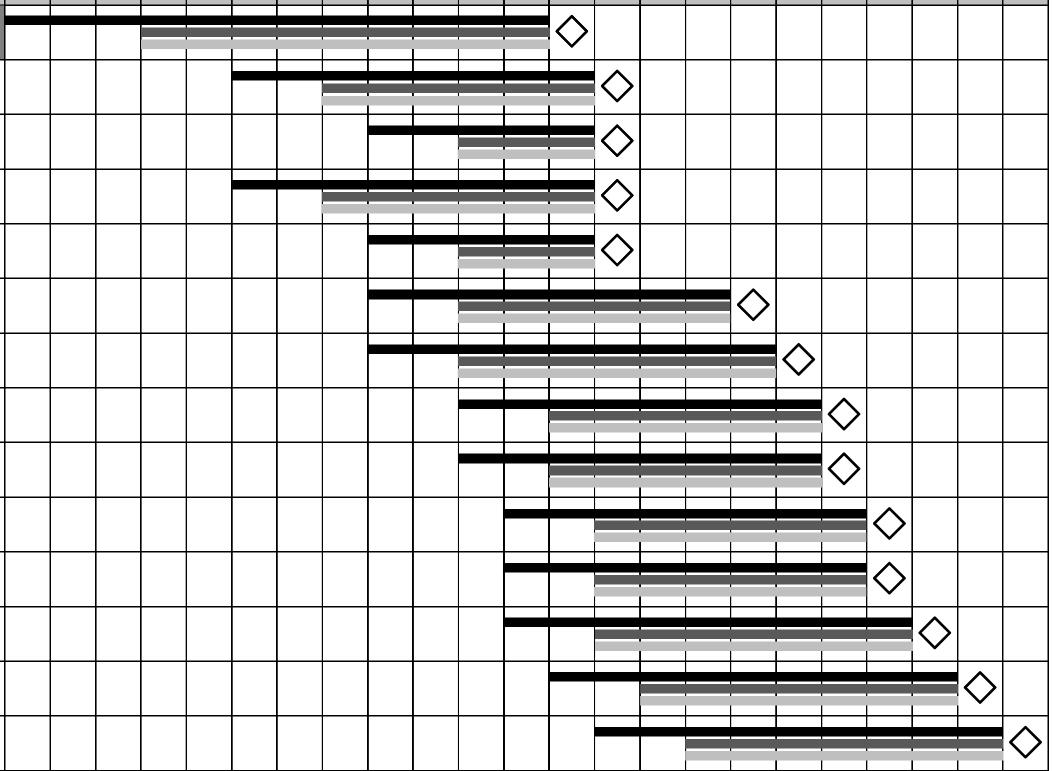
Figure 36: Resource cards for the specific complexity levels

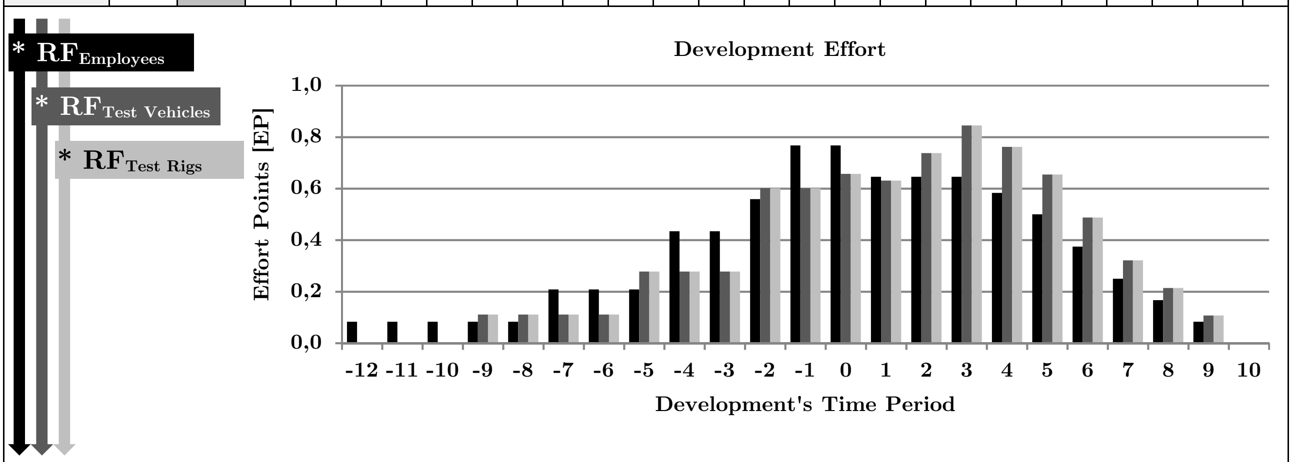
To calculate the development effort [EP] at a certain time (e.g. per month), the evaluated product portfolio (see Table 37) is connected with the resource cards, regarding product's time to market. Then, the particular efforts at a certain time are summed-up. Furthermore, to calculate the amount of required resources at a certain time, the summed-up amount of effort points is multiplied with the specific resource factor (RF). This methodology was applied in the case study and the results are shown in Table 42. It can be seen that employees' maximum is at time T-1 and T0. However, test vehicles' and test rigs' maximum are at time T3.

This methodology enables the user to investigate, where the peaks and lows are and which factors are responsible for that. Further, this is the basis for the application of a specific complexity strategy to optimize company's complexity level.

Table 42: Calculation of project's development effort over time

ID	TtM	CG	WF	Development's time period																						
				-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
1	T0	L	1.0																							
2	T1	DM	0.5																							
3	T1	DS	0.2																							
4	T1	DM	0.5																							
5	T1	DS	0.2																							
6	T4	DM	0.5																							
7	T5	DL	0.75																							
8	T6	DM	0.5																							
9	T6	DM	0.5																							
10	T7	DM	0.5																							
11	T7	DM	0.5																							
12	T8	DL	0.75																							
13	T9	DL	0.75																							
14	T10	DL	0.75																							
Results Development Effort [EP]		PPCI	**7.9**																							
		Σ	**7.9**	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.4	0.4	0.6	0.8	0.8	0.6	0.6	0.6	0.6	0.5	0.4	0.3	0.2	0.1	0
		Σ	**7.9**	0	0	0	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.6	0.6	0.7	0.6	0.7	0.8	0.8	0.7	0.5	0.3	0.2	0.1	0
		Σ	**7.9**	0	0	0	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.6	0.6	0.7	0.6	0.7	0.8	0.8	0.7	0.5	0.3	0.2	0.1	0
Results Resources [N]		Σ	**95**	1	1	1	1	1	3	3	3	5	5	7	9	9	8	8	8	7	6	5	3	2	1	0
		Σ	**71**	0	0	0	1	1	1	1	3	3	3	5	5	6	6	7	8	7	6	4	3	2	1	0
		Σ	**71**	0	0	0	1	1	1	1	3	3	3	5	5	6	6	7	8	7	6	4	3	2	1	0





Explanation:

◇ TtM	Time to Market	CG	Complexity Group	WF	Weighting Factor
■	Employees	■	Test Vehicles	■	Test Rigs

Complexity in product development is characterized by 3 categories: Product, process and product portfolio. These categories have a direct influence on the amount of required resources and their planning. Thus, all 3 categories have to be considered for resources' calculation. A detailed complexity planning increases transparency and enables the management to simulate different development scenarios, including the calculation of the amount of required resources, to identify the optimum.

The already described methodology for resources' calculation and planning is mainly based on the product portfolio and its complexity (PPCI).

In the next step, the categories product and process are added to this methodology, by using a complexity vector, developed by Vogel and Lasch (2015, pp. 126-128). The complexity vector $\overrightarrow{\mathrm{CI}}$ consists of 2 dimensions: Product Complexity Index (PDCI) and Process Complexity Index (PRCI). The 2 dimensions have the same weighting.

$$\overrightarrow{\mathrm{CI}} = \binom{\mathrm{PDCI}}{\mathrm{PRCI}}$$

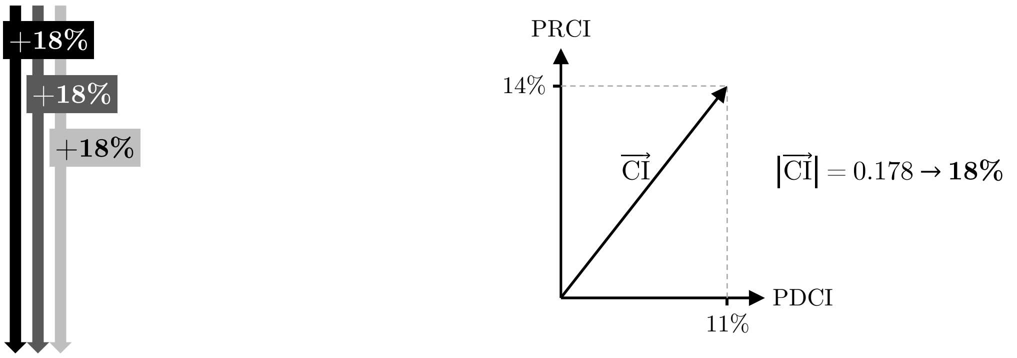
Vector $\overrightarrow{\mathrm{CI}}$ is visualized in the vector space. The vector's length $\left|\overrightarrow{\mathrm{CI}}\right|$ represents development project's complexity and is a multiplicator to combine the 2 complexity dimensions PDCI and PRCI with the PPCI. For the application of a specific complexity strategy, the effects can also be visualized with complexity vector's methodology. For example, the distance between 2 complexity vectors describes the proportion for complexity reduction or increase. The distance is calculated with Pythagoras' theorem (Vogel and Lasch, 2015, p. 127).

$$\left|\overrightarrow{\mathrm{CI}_{12}}\right| = \sqrt{(\mathrm{PDCI}_1\text{-}\mathrm{PDCI}_2)^2 + (\mathrm{PRCI}_1\text{-}\mathrm{PRCI}_2)^2}$$

Next, the complexity vector methodology is applied to the powertrain case study. In the first step of complexity evaluation, a PDCI with 11% (see subsubsection 7.3.3.1) and a PRCI with 14% has been calculated (see subsubsection 7.3.3.2). Based on the PDCI and PRCI, the complexity vector $\overrightarrow{\mathrm{CI}}$ is generated (see Table 43). Then, vector's length $\left|\overrightarrow{\mathrm{CI}}\right|$ is calculated and represents project's complexity as a multiplicator. Thus, the length of $\left|\overrightarrow{\mathrm{CI}}\right|$ is directly associated to development's efforts and the amount of required resources. According to Vogel and Lasch (2015, p. 127), the amount of required resources in total is directly proportional to the length of $\left|\overrightarrow{\mathrm{CI}}\right|$ and the PPCI. The length of $\left|\overrightarrow{\mathrm{CI}}\right|$ is 18%. Thus, the already calculated amount of current project's (project #2) resources in total and at a certain time and based on PPCI have to be multiplied by 18% to combine the 2 dimensions PDCI and PRCI with the PPCI (see Table 43).

Table 43: Complexity vector's influence on the amount of required resources

			Development's time period																						
			-12	**-11**	**-10**	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Amount of Resources [N]	Σ	**95**	1	1	1	1	1	3	3	3	5	5	7	9	9	8	8	8	7	6	5	3	2	1	0
	Σ	**71**	0	0	0	1	1	1	1	3	3	3	5	5	6	6	7	8	7	6	4	3	2	1	0
	Σ	**71**	0	0	0	1	1	1	1	3	3	3	5	5	6	6	7	8	7	6	4	3	2	1	0



Results Resources [N]	Σ	**112**	1	1	1	1	1	4	4	4	6	6	8	11	11	9	9	9	8	7	6	4	2	1	0
	Σ	**84**	0	0	0	1	1	1	1	4	4	4	6	6	7	7	8	9	8	7	5	4	2	1	0
	Σ	**84**	0	0	0	1	1	1	1	4	4	4	6	6	7	7	8	9	8	7	5	4	2	1	0
Explanation:			Employees										Test Vehicles									Test Rigs			

This methodology is used during the product planning phase within the product development process. After resources' calculation and planning, the results are compared with project's objectives and the amount of available resources, because the amount of resources within a project is limited. If the results are conform to project's objectives and the amount of available resources, the next step is to procure the required resources. If the calculation and planning are not conform, the application of specific complexity strategies is necessary to optimize the results. In this case study, the calculated amount of required resources was conform to project's objectives and did not exceed the amount of available resources. Thus, the application of a specific complexity strategy to optimize the results was not necessary.

During this research, the new complexity management approach was applied in further development projects with a bigger product portfolio (e.g. projects with more than 100 product variants). In these projects, the calculated amount of resources exceeded the amount of available resources. Thus, the application of specific complexity strategies was necessary to achieve project's objectives and to be conform to the available amount of resources. After complexity strategy's application, the calculated amount of resources was compared with project's objectives and the amount of available resources. This process was done in an iterative cycle to optimize the calculated amount of required resources in comparison with project's objectives and the amount of available resources.

7.3.5 Stage 4 – Application of complexity strategies

Complexity, variety and the amount of required resources are closely connected. However, the amount of resources within a development project is restricted. If the calculated amount of resources does not match the available resources, the management has to optimize product development's complexity level.

Complexity strategies are used to optimize company's complexity. In literature, a vast number of different single approaches for managing complexity are described (Gießmann, 2010, pp. 57-70) and applied in science and practice. However, there is no specific instruction, which approaches are the most effective for managing a specific complexity problem. It depends on the particular situation and must be planned company-specific. Generally, the approaches can be divided in 4 categories according to their focus: Product, product portfolio, process and organization (Gießmann, 2010, pp. 57-70). The approaches are mainly used for complexity reduction, mastering and avoidance. According to Vogel and Lasch (2015, p. 123), Table 44 presents an overview about the different approaches and their main purposes.

Table 44: Applied single approaches for complexity management

Focus	**Approaches**	**Complexity strategies**		
		Reduction	Mastering	Avoidance
Product	Modular concept	+ + +	+ +	+
	Modular system	+ + +	+ +	+
	Standardization	+ + +	+	+ +
	Using same parts	+ + +	+	+ +
	Platform concept	+ + +	+ +	+
	Differential construction	+ + +	+ +	+
	Integral construction	+ + +	+ +	+
Product portfolio	Packaging	+ + +	+ +	
	Reducing product range	+ + +		+ +
	Reducing of customers	+ + +		
Process	Postponement concept	+ + +	+ +	+
	Standardization of processes	+ + +		+ +
	Modularity of processes	+ + +	+ +	+
Organization	Delayering	+ + +		
	Empowerment	+ + +		
Explanation	+ + + Priority 1 + + Priority 2 + Priority 3			

For example, product standardization can be used to reduce the PDCI or process standardization and modularization to reduce the PRCI. Another example is the application of the complexity strategy reducing product range to reduce the PPCI of a project. For further explanation and to increase reader's understanding about the application of different complexity strategies in the specific complexity indices, Vogel and Lasch (2015, pp. 123-125) describe some examples in their publication.

7.4 Conclusion and outlook

During the last years, customer's requirements for individualized products and the increasing dynamics in innovation and technology lead to an increased product variety and complexity in many industrial branches, especially the automotive industry (Wildemann, 2005, p. 34; Schuh, Arnoscht and Rudolf, 2010, p. 1928; Klug, 2010, p. 41). As a result, the companies have changed their product portfolio (Götzfried, 2013, p. 31). For company's success, it is fundamental to bring new products quickly to the market (Augusto Chauchick Miguel, 2007, p. 617) and with customized settings (Lübke, 2007, p. 2). Thus, more and more different products have to be developed and produced, which leads to an increased effort in product development and production (Klug, 2010, p. 41). Product development is one of the most complex and nontransparent tasks and uncertain processes within a company (Bick and Drexl-Wittbecker, 2008, p. 20; Davila, 2000, p. 386). In product development, the amount of required resources is associated with product's variety and complexity (Bohne, 1998, pp. 9-10). However, the available resources are limited (Zich, 1996, p. 10). Thus, an approach that combines resource planning and complexity management is required.

This chapter's purpose was to close the research gap by developing a praxis-oriented complexity management approach for resource planning in variant-rich product development. The approach was developed based on a detailed literature research and applied on a recent development project in the automotive industry. Product development is characterized by the 3 complexity categories product, process and product portfolio. The new approach combines product development's complexity categories and resource planning principles, because complexity and the amount of resources are directly associated.

Before developing a new approach, the existing literature must be identified, analyzed and systematically evaluated (see subsection 7.2.4). For this chapter, 4 research questions are described, which will be answered in the following manner. The first research question is focused on "What different approaches for complexity management currently exist in scientific literature". As a result, 48 complexity management approaches exist in literature in the time period between 1992 and 2015. The second research question attends to "What focus and structure do the existing approaches have". In the next step, the identified approaches are analyzed according to their focus and structure. More than 50% of the existing approaches are focused on general in manufacturing companies. The remaining approaches are separated in other fields, such as product development, procurement, production, logistics, internal supply chain and distribution. According to their structure (see Table 35), more than 70% of the approaches contain the 2 parts complexity analysis and determine complexity strategy and more than 40% contain the part complexity evaluation. Thus, these parts have to be considered in a new complexity management approach. After literature's identification and analysis, the existing literature was evaluated based on its content and applicability for resource planning to answer the third research question: "What approaches contain information about resource planning and are applicable for practice?" As a result, there are 7 approaches in literature, which contain information about complexity planning, but there is only 1 approach, which is applicable for resource planning. However, the approach from Vogel and Lasch (2015, pp. 109-130) comprises a broader field and the order of the different stages is not feasible in practice. For resource planning in practice, a more focused approach is needed. To answer the fourth research question “What different stages are necessary for a praxis-oriented complexity management approach for resource planning in variant-rich product development?” a new and structurally optimized complexity management approach, especially for the field resource planning was developed, based on Vogel and Lasch’s findings, to cover this literature gap. It is presented in section 7.3 of this chapter. It provides a 4-stage complexity management approach and encourages the reader to analyze and evaluate product development’s complexity. Furthermore, the amount of required resources can be calculated and planned. Then, the results can be compared with project’s objectives and the amount of available resources. As a result of this comparison, specific complexity strategies can be applied for complexity’s and resources’ optimization.

The approach was applied in the automotive industry, especially in the hybrid powertrain development department of an automotive company to verify the research results. Future research may also include other sectors, such as consumer electronics, engineering or toy industry to verify the approach or to enhance the methodology for resource planning. For practice, it is important to have an overview about different approaches for complexity driver’s identification and analyzation, especially in the categories product, process and product portfolio. In this chapter, a certain amount of approaches is described (see subsection 7.3.2; Table 36). A more general overview does not exist yet. Furthermore, the literature should be analyzed for further methodologies for calculating specific complexity weighting factors analogously to the described methodology in subsection 7.3.3. In this chapter, the weighting factors are developed according to complexity, development time and effort.

8 Conclusion and outlook

8.1 Summary

The objective of this dissertation is to develop a **complexity management for variant-rich product development**. The thesis comprises 5 main parts, starting with a literature review about complexity drivers in the manufacturing industry and an empirical research, focused on complexity drivers in product development and their effects on company's complexity, to compare literature results with the empirical findings. Next, the different single approaches for managing complexity and their targeted strategies are described based on literature. To compare the literature results with the real world, an empirical research regarding single approaches' application for managing complexity in product development is also conducted. Based on these results and further literature research, focusing on approaches for managing complexity, a new general approach for complexity management in variant-rich product development is developed. Next, this general approach is modified for company's specific context or problem. Thus, a new complexity management approach for resource planning in variant-rich product development is generated.

Before starting this research, the existing literature regarding the following issues was reviewed and gaps for future research were identified:

- Complexity drivers in manufacturing companies and along the value chain, especially in product development and their effects on company's complexity.
- Complexity strategies and their applied single approaches for managing complexity.
- Approach(es) for complexity management, especially in variant-rich product development.
- Complexity management approach for resource planning, especially in variant-rich product development.

For the literature research, the methodology of Fink (2014, pp. 3-4) was used, starting with the definition of the research questions and the selection of the required sources. Then, the search terms, the practical and the methodological screening criteria were defined and applied to identify and select the relevant literature from the entity of found literature. To extend the amount of relevant literature, the literature research was conducted in English- and German-language literature and databases. The following 8 English and German databases were used: EBSCOhost, Emerald, GENIOS/WISO, Google Scholar, IEEE Xplore, JSTOR, ScienceDirect and SpringerLink. The search terms were formulated in English and German based on the key words and their synonyms, as well as the Boolean operators, such as AND, OR, NOT and NEAR. The search resulted in a certain amount of literature sources, but only a few are relevant. The searched literature was analyzed, evaluated and synthesized based on the qualitative content analysis, to identify the relevant literature sources. The time period for the different literature researches was restricted between 1900/01/01 and 2015/12/31, because the empirical study was performed in the years 2015 and 2016.

To compare literature's results with the real world to identify commonalities and differences, an empirical research was conducted based on the methodology of Flynn *et al.* (1990, pp. 253-255). The methodology starts with the determination of the theoretical foundation and the research design. Then, data collection method and sample description for research's implementation are selected. Next, the collected data is processed and analyzed before research report's publication. In this empirical research, the research design survey was selected and a standardized questionnaire with 16 questions and a fixed response possibility was applied for data collection. The data was collected from a stratified random sample, which was taken out of a given population of 17,862 manufacturing companies, located in Germany with more than 50 employees. In 2015 and 2016 the questionnaire was sent to 3,086 companies, exclusive of service and printing companies, by e-mail in 2 stages. Before starting this empirical research, a first version of the questionnaire was pretested by 40 experts from the potential target group to check and refine the wording, understanding, relevance, the measurement instrument, as well as questionnaire's length and the time for questionnaire's responding. For answering the empirical research questions, the empirical data was analyzed by using statistical data analysis techniques.

According to Fink (2014) and Flynn *et al.* (1990), literature and empirical research starts with the determination of the research questions. In total, 20 research questions were formulated in this thesis and separated in 14 literature research questions and 6 empirical research questions. The research questions are answered as follows:

Answering the first 3 research questions **(RQ1** to **RQ3)**, the identified literature sources ($N_{identified}$: 11,425) regarding complexity drivers in manufacturing companies were analyzed and synthesized (see subsection 3.3.1). In total 235 relevant literature sources in the time period 1991 to 2015 were found. However, no relevant literature sources concerning the issue complexity drivers were identified before 1991. The reasons could be attributed to complexity management's evolution over the last 25 years and the principal definition and understanding of the term "complexity driver". The analysis of the overall trend of the literature regarding the issue complexity drivers shows an increased interest throughout the last 10 years. Between 2004 and 2015, 74% of all publications were published. More than 50% of all publications about complexity drivers were published in journals and PhD theses. Thus, complexity drivers have a high importance in scientific research. Before analyzing the identified literature, the literature was separated in the following 8 different fields: Product Development (PD), Procurement/Purchasing (PC), Logistics (L), Production (PR), Order Processing/Distribution/Sale (OPD), Internal Supply Chain (SC), Remanufacturing (R) and General in Value Chain (VC). The analysis shows that the amount of publications about complexity drivers in all 8 different fields has also increased over the last 10 years. Previous literature studies about complexity drivers have been done by Meyer (2007, pp. 182-183), Serdarasan (2011, pp. 793-795; 2013, pp. 534-535) and Wildemann and Voigt (2011, pp. 44-52, 63-72, 113-170).

In literature, several different definitions of complexity drivers are described by 36 authors (**RQ1**) (see subsection 3.3.2). Based on their content, the definitions can be assigned to 5 main categories: Factors, indicators, sources, parameters/variables and symptoms/phenomenon. As a result, there is no universal understanding of the term complexity driver, but the identified definitions tend towards similar definitions. To generate a more general definition of complexity drivers, the existing definitions were analyzed by identifying their hypernyms and differentia. Several different hypernyms for the genus term complexity driver exist in literature, but only the term factor covers the general understanding of a complexity driver in total. Then, the existing differentia were clustered into 5 groups based on their commonalities and differences. Based on these groups and in combination with the hypernym term factor, the following general definition of complexity driver was generated: *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. Complexity drivers are influenced by one another, that is by internal or external drivers, and cannot be reduced completely to another one.*

In summary, the new definition summarizes all information from already existing definitions and is applicable general in manufacturing companies and in all parts along the value chain.

A specific and target-oriented complexity management is based on complexity driver's identification, visualization and operationalization. Several different methods for identification, operationalization and visualization of complexity drivers are applied in literature (**RQ2**) (see subsection 3.3.3). In literature, 21 different approaches for complexity driver's identification exist and focus on different fields in the company and along the value chain. The most applied approaches are expert interviews, process analysis and system analysis. For complexity driver's operationalization and visualization, 8 different approaches could be identified in the existing literature. However, a clear assignment of the different approaches to operationalize and visualize complexity drivers was not possible in all cases. As a result, the most applied approach in both areas is the classification- and driver-matrix.

As already mentioned, complexity drivers have a direct influence on the company and the value chain. Complexity drivers can be separated in internal and external drivers, depending on their origin. In literature, more than 480 different internal and external complexity drivers in manufacturing companies and along the value chain were found during this research (**RQ3**) (see subsection 3.3.4). For clustering the 486 complexity drivers, a new superior classification system without overlaps between the different driver categories was developed based on existing classification systems. The new and general classification system can be applied in manufacturing companies and in all parts along the value chain. All complexity drivers, which occur in the company and along the value chain, can be allocated to this superior classification system. In summary, it consists of 3 main groups (external complexity, internal complexity and general complexity), 4 subcategories (society complexity, market complexity, internal correlated complexity and internal autonomous complexity) and 22 main complexity driver categories depending on their origin, characteristics and influences on other drivers. The identified 486 complexity drivers were clustered into these categories and groups. The assignment was done depending on the complexity driver's origin, characteristics and influences on other drivers.

In summary, chapter 3 presents a systematic, explicit and reproducible literature review about complexity drivers in manufacturing companies and along the value chain over a period of 25 years (1991-2015). It answers the research questions 1 to 3 and fulfills all requirements of a literature review in total. Further, the afore-mentioned gaps in literature (see section 2.2) are closed.

This thesis is mainly focused on product development. In the next step, the complexity drivers in product development and their effects on company's complexity were identified and analyzed. Furthermore, the results were compared with the real world by an empirical research in the German manufacturing industry. Before starting an empirical research, the existing literature regarding complexity drivers in product development and their effects, as well as previous empirical studies must be reviewed. For this literature review, the research questions **RQ4** and **RQ5** were defined (see section 1.2) and answered.

Regarding to the fourth research question (**RQ4**), 17 publications concerning complexity drivers in product development were found between 1998 and 2015 (see subsection 4.2.2). However, no publications are found before 1998. Between 2010 and 2015, 65% of the publications were published and show an increased interest in scientific research throughout the last years. Furthermore, 107 different complexity drivers in product development were found in literature. The identified complexity drivers were clustered in different main complexity driver categories depending on their origin, characteristics and influence on other drivers. As a result of complexity drivers' clustering, 28 external (26%), 30 internal correlated (28%) and 49 internal autonomous complexity drivers (46%) were found in literature. Most of the identified complexity drivers were assigned to the main group internal complexity. Regarding the effects of high complexity on company's complexity, in literature, several effects are described and divided in different categories. In general, most of the mentioned complexity effects can be aggregated in 4 main categories: Time, quality, costs and flexibility.

Answering the fifth research question (**RQ5**), the literature about previous empirical studies in the field complexity management was reviewed. In total, 26,699 literature sources were identified and analyzed. As a result of literature's analysis, 72 empirical studies regarding complexity management in various industry branches and regions/countries already exist (see subsection 4.2.3). The studies are focused on different fields in the company and along the value chain and were conducted between 1999 and 2015. The studies were analyzed and synthesized regarding their content, research objectives, focus, field of industry, region/country, research period and applied data collection methodology. Most of the empirical studies are focused on the fields general in manufacturing companies (N: 32) and internal supply chain (N: 16). Regarding the field product development, only 6 empirical studies were performed with different objectives between the time period 2005 and 2013. A further objective was to identify all previous studies, which contain the issue 'complexity drivers and their effects on company's complexity' during the last years. The literature research resulted in 13 different studies, focused on complexity drivers. However, an empirical study in the field product development in manufacturing companies in Germany and with focus on complexity drivers does not exist yet. This gap was closed by presenting a systematic, explicit and reproducible empirical research (see sections 4.3 and 4.4).

For this empirical research, 4 additional research questions (**RQ6** to **RQ9**) (see section 1.2), called empirical research questions, were determined and answered in the following way. For data collection, 3,086 manufacturing companies with more than 50 employees, located in Germany, were questioned through a standardized questionnaire. The companies were taken from the Amadeus database, where all German companies are listed. The questionnaire was sent by e-mail to them. In the email, the companies were asked to send the questionnaire to an experienced employee in the product development department. In total, 295 questionnaires were answered completely. Industry's range contained 11 different fields of industry. According to their characteristics, the identified industry branches were clustered in 4 industry clusters: Technical industries, resource industries, consumer goods industry and others. The technical industry is the largest industry cluster and comprises about 60% of the respondents: Engineering (30.5%), metal (10.5%), electrical and optics (9.8%), as well as automotive (8.1%). For result's validation, the percentage of the empirical research was compared with the percentage of the Amadeus database to identify commonalities and differences. In this research, the percentage of empirical research and database are very close in all industry clusters. Thus, the empirical findings are representative and can be generalized. Next, the number of employees and the position profile of the respondents were analyzed. With 61.8%, the small and middle-sized companies formed the biggest group in the empirical research. Larger companies with more than 250 employees represent 38.2%. The analysis of the respondent's position profile shows that 80% of the respondents can be assigned to the category upper management. This category comprises the following 3 groups: Presidents, CEOs and COOs (18.0%); directors and division managers (26.1%); senior managers and department managers (35.9%). Based on these results, it can be concluded that small and middle-sized companies are highly interested in empirical studies regarding complexity management and especially in product development. In addition, complexity in product development is an important issue for company's higher management

To answer the sixth research question (**RQ6**), product development's characteristics of the participating companies are analyzed regarding product and variant range; length of product life cycle and product development process; amount of applied components, materials, technologies and processes; the height of the own value adding percentage, as well as organization's influence on product development's complexity (see subsection 4.4.1). Approximately 75% of the companies are characterized by a medium and big product and variant range. Beyond, more than 50% of the developed products have a life cycle length over 72 months, but approximately 70% of the respondents specified that the length of product development process is less than 25 months. Furthermore, the majority of companies indicate that their products consist of many different components, materials, as well as technologies. Regarding the product development process, the respondents answer that their process consists of many different process steps. In addition, the percentage of the own value adding activity in product development was analyzed. However, there was no explicit tendency recognizable. To analyze organization's influence on product development's complexity, the respondents were questioned about their evaluation. More than 75% of the respondents specified that the organization has no negative influence on product development's complexity. Comparing this result with literature, there is a discrepancy, because in literature, organizational complexity drivers are responsible for increasing complexity in the company and especially in product development. It would be interesting to investigate the reasons for this discrepancy within a further empirical research (e.g. investigation through expert interviews).

Next, the empirical data regarding complexity drivers in product development was analyzed and evaluated for answering the seventh research question (**RQ7**) (see subsection 4.4.2). Based on the statistical analysis, some industries are influenced by more complexity drivers than other industries. Furthermore, some complexity drivers occur in most fields of industry and thus are more important than other drivers. Generally, complexity in product development is mostly influenced by external complexity drivers. As a further result, different fields of industry are influenced by individual main complexity drivers. Regarding complexity driver's aggregation, a correlation analysis was conducted to identify the relationships and interdependencies between the different drivers. As a result of this analysis, strong correlations between different complexity drivers occur in 16 categories. Beyond, very strong correlations occur between 2 categories. Based on the correlation analysis, a factor analysis with varimax rotation was used for complexity driver's aggregation. As a result of the factor analysis, 7 factors were identified, which are reflecting the complexity drivers: *Company's complexity, product and technology complexity, customer's complexity, market complexity, supply complexity, environmental and society complexity,* as well as *target complexity.*

Answering the eighth research question (**RQ8**), complexity driver's influences on product development's complexity in the 4 categories time, quality, costs and flexibility were analyzed. As a result of this empirical research, high complexity has mostly a strong or very strong effect on 4 attributes: Product development time, adherence to deadlines in product development, product quality and product development's costs in general. Furthermore, high complexity has a strong effect on the development time in nearly all industry branches and high complexity has a higher effect in technical industries than in others.

In the last step of this emipirical research, the empirical findings about the complexity drivers are compared with the literature results to identify the significant differences and commonalities and to answer the ninth research question (**RQ9**) (see subsection 4.4.3). As a result of this comparison, in literature, 108 different complexity drivers are described in total without prioritization by the authors. In contrast, in this empirical study only 30 complexity drivers with a strong or very strong influence on product development are mentioned and prioritized by experts.

Summarizing the results of this empirical research, the existing gap in scientific research is closed in chapter 4 by presenting an empirical study in the field product development in the manufacturing industry of Germany and with the focus on complexity drivers, including the identification and analysis of complexity drivers and their effects on company's complexity, as well as a comparison between literature and practice.

After complexity driver's identification, analysis and evaluation, as well as a comparison between literature and the real world, the applied single approaches for managing complexity and their targeted strategies have to be identified based on literature. Furthermore, the literature results also have to be compared with the real world by an empirical study also in the German manufacturing industry. Before starting this empirical research, the existing literature regarding the applied single approaches and their targeted strategies has to be reviewed first. For this literature study, 3 research questions are defined (**RQ10** to **RQ12**) (see section 1.2).

For answering research question 10 (**RQ10**), the researched literature (130,722 identified literature sources) was analyzed and synthesized regarding specific single approaches for managing complexity and their targeted strategy. The synthesizing process resulted in 288 relevant literature sources in the time period between 1962 and 2015. In scientific literature, 15 different single approaches for managing complexity in the company and along the value chain are described. The approaches are divided in 4 categories according to their focus: Product, product portfolio, process and organization. In the category product, the most important single approaches are modular concept, modular system, standardization, using same parts, platform concept, differential construction and intergral construction. In the second category product portfolio, the approaches packaging, reducing product range and reducing of customers are referred to in literature. The third category comprises the single approaches, focused on process: Postponement concept, standardization of processes and modularity of processes. In the last category, the approaches regarding organization are delayering and empowerment. According to their occurrence in literature, the most referred and applied single approaches are modular concept, modular system, standardization, using same parts and platform concept. Another result of this literature study is that literature focuses more and more on the different complexity management single approaches over time. Generally, the literature sources are published between the time period 1962 and 2015. However, the amount of publications regarding all single approaches has increased between 2005 and 2015.

Thus, there is an increasing interest in science regarding the specific complexity management approaches during the last 10 years.

Generally, the single approaches are focused on 6 different strategies or objectives (**RQ11**): Complexity reduction, mastering, avoidance, increasing, outsourcing and general for complexity management. As a result of this literature analysis, all approaches are assigned to more than one purpose or strategy. However, the approaches are mostly used for complexity reduction. Thus, this is the main complexity strategy for complexity management single approaches.

Regarding the twelfth research question (**RQ12**), the already identified empirical studies in the field complexity management (see **RQ5**) were analyzed again to identify empirical studies with focus on the practical application of specific single approaches for managing complexity and their targeted strategy. As a result of literature's analysis, an empirical research focused on this issue does not exist yet. This gap was closed by also presenting a systematic, explicit and reproducible empirical research (see sections 5.3 and 5.4).

For this empirical research, 2 additional research questions (**RQ13** and **RQ14**) (see section 1.2) were determined. The empirical study was conducted in the same way as already mentioned. The data regarding the complexity management approaches, their objectives and practical application was analyzed and evaluated to answer the thirteenth research question (**RQ13**). For complexity management, 15 different approaches focused on 5 different strategies were generally applied in practice. However, 9 different approaches are predominantly known and used for complexity management in the manufacturing industry of Germany: Modular concept, modular system, standardization, using same parts, platform concept, reducing product range, standardization of processes, modularity of processes and empowerment. Next, the results are compared within the 4 industry clusters. As a result of this comparison, some industry branches apply specific approaches more often than other branches. Next, the data was analyzed according to approches' targeted strategy. The single approaches are mainly used for complexity reduction or mastering. However, no explicit tendency towards 1 specific strategy can be identified. Analyzing these results regarding the different fields of industry and industry clusters, the results are equal.

After analyzing the empirical data, the empirical findings regarding the approaches for complexity management are compared with literature to answer research question 14 (**RQ14**) (see subsection 5.4.3). In literature, the approaches are focused mostly on complexity reduction. In this study, the approaches could not be assigned to a specific complexity strategy. No explicit tendency can be identified.

In chapter 5, the existing gap in literature is closed by presenting a general literature overview about the different single approaches, their focus and targeted strategies. Furthermore, a systematic, explicit and reproducible empirical research regarding the practical application of specific single approaches for managing complexity and their targeted strategy, including a comparison between empirical findings and literature is shown.

As already mentioned in section 1.2, an approach for complexity management is needed to bring the relevant steps for complexity handling, including complexity driver's identification, analysis and evaluation, as well as the complexity strategies and their applied single approaches, in a sequence. In this thesis, a praxis-oriented approach for managing complexity in variant-rich product development is developed based on literature. Further, the general approach is modified for resource planning. Before developing a new approach, existing literature regarding complexity management approaches has to be identified, analyzed and evaluated first. An overview about the existing complexity management approaches, including their focus, structure, target and applicability for resource planning, has to be described. Based on literature's findings, a new approach is developed. For literature analysis, several research questions are determined (**RQ15** and **RQ20**) (see section 1.2) and answered as follows:

Responding to the already mentioned research questions, the existing literature (13,085 identified literature sources) was analyzed and synthesized (see subsections 6.2.2 and 7.2.4). The literature search resulted in 47 relevant approaches in the time period between 1992 and 2014 (**RQ15** and **RQ17**). More than 50% of the existing approaches are focused on general in manufacturing companies. Only 3 approaches are focused on product development. The identified approaches are analyzed and described according to their structure and targets (**RQ16** and **RQ18**). Based on this analysis, 7 stages can be identified and are applied in literature for complexity management: Complexity analysis, complexity evaluation, determination of complexity strategies, determination of appropriate complexity instruments, complexity planning, complexity management's implementation and complexity controlling. The most applied stages are determination of complexity strategies, complexity analysis and evaluation. However, there is no approach, which consists of all stages. In literature, complexity management in product development is determined by product complexity, process complexity and product portfolio complexity, so the literature was analyzed according to these categories. Most of the existing approaches have no explicit target or focus. Only 1 approach exists with a focus on all mentioned complexity categories. Further, the identified approaches were evaluated based on 11 different criteria, which are important for a complexity management approach, to identify strengths, weaknesses and deficits. As a result of the analyzing and evaluation process, there is no approach, which fulfills all requirements in total or partially. Based on the existing literature, a new and general 4-stage approach for complexity management in variant-rich product development, which consists of all stages and categories and fulfills all criteria in total or partially, was developed to cover this research gap (see chapter 6).

In the next step, the previously existing approaches, as well as the new and general complexity management approach from chapter 6 were analyzed and evaluated based on their structure and applicability for resource planning (**RQ19** and **RQ20**). This includes the complexity management's objectives, product development's characteristics and objectives, as well as the principle for resource planning and the applicability in product development. The analysis and evaluation process resulted in the new general approach for complexiy management, which was developed based on the aforementioned research gap and fulfills all requirements. However, the order of the different stages was not feasible in practice. Therefore, a new and structurally optimized complexity management approach for resource planning, especially in variant-rich product development, is needed to increase particability in practice. Within this thesis, this research gap is closed by developing a complexity management approach, especially for resource planning in variant-rich product development (see chapter 7).

8.2 Future research

During this research, several **gaps for future research** were identified and pointed out according to the aforementioned 4 issues from section 8.1.

Regarding the issue **complexity drivers**, the literature review from chapter 3 was focused only on the manufacturing industry. Future research may also include other sectors or industries, such as financing and/or insurance. It would also be interesting to compare the research results from other sectors with the results of this thesis. In literature, several approaches for complexity driver's identification, operationalization and visualization exist. These approaches can be used as a basis to gain first implications about complexity drivers, their identification, operationalization and visualization. However, an evaluation according to their practical application does not exist yet. Further research will be needed to create helpful advice for practitioners to detect complexity issues, as well as to present methodological support to detect causes of complexity and their effects. Further, the different approaches for complexity driver's identification, operationalization and visualization should be evaluated by the practice within an empirical research according to the following 3 categories: Amount of work, data volume and level of difficulty. Also, the different approaches should be evaluated regarding their specific fields of application. This information could encourage the user to find the right approach for his/her specific field of interest. Further research may also include finding an approach to identify and analyze the most important complexity driver's categories.

In chapter 4 and 5, the empirical results regarding **complexity drivers in product development and their effects on company's complexity**, as well as the **application of specific single approaches for managing complexity and their targeted strategies** are compared with the literature to identify commonalities and differences. Further research should analyze the differences between theory and practice more in detail and the empirical findings should be used for further discussions und evaluations in literature. This empirical study was focused on the manufacturing industry of Germany in 2015 and 2016. Future research may also include other countries and sectors, as well as companies with less than 50 employees. It would be interesting to compare the empirical results from this study with the results from a further study, which is conducted in other fields of industry or countries/regions. In addition, the companies should compare and evaluate their complexity drivers with those described in literature to question their own identified complexity drivers. Based on the empirical findings, further discussions and evaluations can be performed in literature. Furthermore, the development of complexity drivers and their importance for a company over time would also be interesting. Therefore, the same empirical research should be repeated in the future (e.g. 5 to 10 years) to identify differences and commonalities of complexity driver's perception between now and the future. In literature, organizational complexity drivers are responsible for increasing complexity in the company and especially in product development. Comparing this with the empirical results, there is a discrepancy. It would be interesting to investigate the reasons for this discrepancy within a further empirical research (e.g. investigation through expert interviews).

Regarding the issue **approach for complexity management and resource planning** in variant-rich product development, the new approaches were applied in the automotive industry to verify the research results. Future research may also include other sectors, such as consumer electronics, engineering or toy industry to verify the approach or to enhance the methodology for complexity management and resource planning. For practice, it is important to have an overview about different approaches for complexity driver's identification and analysis, especially in the categories product, process and product portfolio. Several approaches are described in this thesis (see subsection 3.3.3 and 7.3.2). A more general overview does not exist yet. Furthermore, the literature should be analyzed for further methodologies for calculating specific complexity weighting factors analogously to the described methodology in subsection 7.3.3. In this work, the weighting factors are developed according to complexity, development time and effort.

Appendix

Table 45: Framework and results of literature collection during the period 1900/01/01 - 2015/12/31 (Part A)

Focus	Database	Search terms	Date	Results
General in manufacturing companies	EBSCOhost	'Komplexitätstreiber' OR (Treiber N3 Komplexität)	16/05/20	0
		'complexity driver*' OR (driver* N3 complexity)	16/05/20	346
	Emerald	"Komplexitätstreiber" OR "Treiber d* Komplexität"	16/05/20	0
		"complexity driver" OR "driver of complexity"	16/05/20	12
	GENIOS/ WISO	"Komplexitätstreiber" OR (Treiber ndj3 Komplexität)	16/05/22	290
		"complexity driver*" OR (driver* ndj3 complexity)	16/05/22	38
	Google Scholar	"Komplexitätstreiber" OR "Treiber d* Komplexität"	16/05/22	507
		"complexity driver*" OR "driver* of complexity"	16/05/22	261
	IEEE Xplore	"Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)	16/05/22	0
		complexity NEAR/3 driver	16/05/22	887
	JSTOR	"Komplexitätstreiber" OR ("Treiber Komplexität"~5)	16/05/23	0
		"complexity driver" OR ("driver complexity"~5)	16/05/23	11
	ScienceDirect	"Komplexitätstreiber*" OR (Treiber W/3 Komplexität)	16/05/23	0
		complexity W/3 driver*	16/05/23	540
	SpringerLink	Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)	16/05/23	294
		Complexity NEAR/3 driver*	16/05/23	424
			Total:	**3,610**
Product Development	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND 'Produktentwicklung'	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'product development'	16/04/06	4
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Produktentwicklung"	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "product development"	16/04/06	2
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND "Produktentwicklung"	16/04/06	42
		("complexity driver*" OR (driver* ndj3 complexity)) AND "product development"	16/04/06	5
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Produktentwicklung"	16/05/06	167
		("complexity driver*" OR "driver* of complexity") AND "product development"	16/05/06	77
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND Produktentwicklung	16/05/06	0
		(complexity NEAR/3 driver) AND (product development)	16/05/06	229
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND "Produktentwicklung"	16/06/06	0
		("complexity driver" OR ("driver complexity"~5)) AND "product development"	16/06/06	4
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Produktentwicklung	16/06/06	0
		(complexity W/3 driver*) AND product development	16/06/06	206
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND Produktentwicklung	16/06/06	100
		(Complexity NEAR/3 driver*) AND "product development"	16/06/06	75
			Total:	**911**

Table 45: Framework and results of literature collection during the period 1900/01/01 - 2015/12/31 (Part B)

Focus	Database	Search terms	Date	Results
Procurement/ Purchasing	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND ('Produktentwicklung' OR 'Einkauf')	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND ('procurement' OD 'purchasing')	16/04/06	5
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ("Beschaffung" OR "Einkauf")	16/04/06	0
		("complexity driver" OR "driver of complexity") AND ("procurement" OR "purchasing")	16/04/06	3
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND ("Beschaffung" OR "Einkauf")	16/04/06	98
		("complexity driver*" OR (driver* ndj3 complexity)) AND ("procurement" OR "purchasing")	16/04/06	13
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ("Beschaffung" OR "Einkauf")	16/05/06	314
		("complexity driver*" OR "driver* of complexity") AND ("procurement" OR "purchasing")	16/05/06	75
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Beschaffung OR Einkauf)	16/05/06	0
		(complexity NEAR/3 driver) AND (procurement OR purchasing)	16/05/06	54
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND ("Beschaffung" OR "Einkauf")	16/06/06	1
		("complexity driver" OR ("driver complexity"~5)) AND ("procurement" OR "purchasing")	16/06/06	11
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND (Beschaffung OR Einkauf)	16/06/06	0
		(complexity W/3 driver*) AND (procurement OR purchasing)	16/06/06	108
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND (Beschaffung OR Einkauf)	16/06/06	169
		(Complexity NEAR/3 driver*) AND (procurement OR purchasing)	16/06/06	117
			Total:	**968**
Logistics	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND 'Logistik'	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'logistics'	16/04/06	8
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Logistik"	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "logistics"	16/04/06	6
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND "Logistik"	16/04/06	110
		("complexity driver*" OR (driver* ndj3 complexity)) AND "logistics"	16/04/06	8
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Logistik"	16/05/06	260
		("complexity driver*" OR "driver* of complexity") AND "logistics"	16/05/06	81
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Logistik)	16/05/06	0
		(complexity NEAR/3 driver) AND (logistics)	16/05/06	45
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND "Logistik"	16/06/06	2
		("complexity driver" OR ("driver complexity"~5)) AND "logistics"	16/06/06	3
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Logistik	16/06/06	0
		(complexity W/3 driver*) AND logistics	16/06/06	73
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND Logistik	16/06/06	143
		(Complexity NEAR/3 driver*) AND logistics	16/06/06	98
			Total:	**837**

Table 45: Framework and results of literature collection during the period 1900/01/01 - 2015/12/31 (Part C)

Focus	Database	Search terms	Date	Results
Production	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND 'Produktion'	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'production'	16/04/06	14
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Produktion"	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "production"	16/04/06	7
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND "Produktion"	16/04/06	118
		("complexity driver*" OR (driver* ndj3 complexity)) AND "production"	16/04/06	0
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Produktion"	16/05/06	379
		("complexity driver*" OR "driver* of complexity") AND "production"	16/05/06	156
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Produktion)	16/05/06	0
		(complexity NEAR/3 driver) AND (production)	16/05/06	161
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND "Produktion"	16/06/06	1
		("complexity driver" OR ("driver complexity"~5)) AND "production"	16/06/06	46
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Produktion	16/06/06	0
		(complexity W/3 driver*) AND production	16/06/06	176
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND Produktion	16/06/06	198
		(Complexity NEAR/3 driver*) AND production	16/06/06	245
			Total:	**1,501**
Order Processing	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND Auftrags*	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'order processing'	16/04/06	1
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND Auftrags*	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "order processing"	16/04/06	1
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND Auftrags*	16/04/06	75
		("complexity driver*" OR (driver* ndj3 complexity)) AND "order processing"	16/04/06	0
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND Auftrags*	16/05/06	223
		("complexity driver*" OR "driver* of complexity") AND "order processing"	16/05/06	14
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Auftrags*)	16/05/06	0
		(complexity NEAR/3 driver) AND (order processing)	16/05/06	480
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND Auftrags*	16/06/06	3
		("complexity driver" OR ("driver complexity"~5)) AND "order processing"	16/06/06	0
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Auftrags*	16/06/06	0
		(complexity W/3 driver*) AND order processing	16/06/06	298
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND Auftrags*	16/06/06	146
		(Complexity NEAR/3 driver*) AND "order processing"	16/06/06	16
			Total:	**1,257**

Table 45: Framework and results of literature collection during the period 1900/01/01 - 2015/12/31 (Part D)

Focus	Database	Search terms	Date	Results
Distribution/ Sale	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND ('Vertrieb' OR 'Verkauf')	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND ('distribution' OR 'sale')	16/04/06	14
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ("Vertrieb" OR "Verkauf")	16/04/06	0
		("complexity driver" OR "driver of complexity") AND ("distribution" OR "sale")	16/04/06	6
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND ("Vertrieb" OR "Verkauf")	16/04/06	101
		("complexity driver*" OR (driver* ndj3 complexity)) AND ("distribution" OR "sale")	16/04/06	14
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND ("Vertrieb" OR "Verkauf")	16/05/06	296
		("complexity driver*" OR "driver* of complexity") AND ("distribution" OR "sale")	16/05/06	163
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Vertrieb OR Verkauf)	16/05/06	0
		(complexity NEAR/3 driver) AND (distribution OR sale)	16/05/06	282
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND ("Vertrieb" OR "Verkauf")	16/06/06	2
		("complexity driver" OR ("driver complexity"~5)) AND ("distribution" OR "sale")	16/06/06	58
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND (Vertrieb OR Verkauf)	16/06/06	0
		(complexity W/3 driver*) AND (distribution OR sale)	16/06/06	225
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND (Vertrieb OR Verkauf)	16/06/06	152
		(Complexity NEAR/3 driver*) AND (distribution OR sale)	16/06/06	306
			Total:	**1,619**
Supply Chain	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND 'Supply Chain'	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'supply chain'	16/04/06	9
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Supply Chain"	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "supply chain"	16/04/06	7
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND "Supply Chain"	16/04/06	79
		("complexity driver*" OR (driver* ndj3 complexity)) AND "supply chain"	16/04/06	8
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Supply Chain"	16/05/06	170
		("complexity driver*" OR "driver* of complexity") AND "supply chain"	16/05/06	87
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Supply Chain)	16/05/06	0
		(complexity NEAR/3 driver) AND (supply chain)	16/05/06	64
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND "Supply Chain"	16/06/06	1
		("complexity driver" OR ("driver complexity"~5)) AND "supply chain"	16/06/06	3
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Supply Chain	16/06/06	0
		(complexity W/3 driver*) AND supply chain	16/06/06	96
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND "Supply Chain"	16/06/06	81
		(Complexity NEAR/3 driver*) AND "supply chain"	16/06/06	97
			Total:	**702**

Table 45: Framework and results of literature collection during the period 1900/01/01 – 2015/12/31 (Part E)

Focus	Database	Search terms	Date	Results
Remanu-facturing	EBSCOhost	('Komplexitätstreiber' OR (Treiber N3 Komplexität)) AND 'Refabrikation'	16/04/06	0
		('complexity driver*' OR (driver* N3 complexity)) AND 'remanufacturing'	16/04/06	0
	Emerald	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Refabrikation"	16/04/06	0
		("complexity driver" OR "driver of complexity") AND "remanufacturing"	16/04/06	0
	GENIOS/ WISO	("Komplexitätstreiber" OR (Treiber ndj3 Komplexität)) AND "Refabrikation"	16/04/06	1
		("complexity driver*" OR (driver* ndj3 complexity)) AND "remanufacturing"	16/04/06	1
	Google Scholar	("Komplexitätstreiber" OR "Treiber d* Komplexität") AND "Refabrikation"	16/05/06	1
		("complexity driver*" OR "driver* of complexity") AND "remanufacturing"	16/05/06	3
	IEEE Xplore	("Komplexitätstreiber" OR (Treiber NEAR/3 Komplexität)) AND (Refabrikation)	16/05/06	0
		(complexity NEAR/3 driver) AND (remanufacturing)	16/05/06	1
	JSTOR	("Komplexitätstreiber" OR ("Treiber Komplexität"~5)) AND "Refabrikation"	16/06/06	0
		("complexity driver" OR ("driver complexity"~5)) AND "remanufacturing"	16/06/06	0
	ScienceDirect	("Komplexitätstreiber*" OR (Treiber W/3 Komplexität)) AND Refabrikation	16/06/06	0
		(complexity W/3 driver*) AND remanufacturing	16/06/06	4
	SpringerLink	(Komplexitätstreiber OR (Treiber NEAR/3 Komplexität)) AND "Refabrikation"	16/06/06	1
		(Complexity NEAR/3 driver*) AND "remanufacturing"	16/06/06	8
			Total:	**20**

Table 46: Results of literature analysis (Part A)

Language of literature source: [1] German [2] English	Content of literature sources based on literature's analysis															
		RQ1	**RQ2 Approach for...**			**RQ3 Information about complexity drivers**										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver' s identification	Complexity driver' s operationalization	Complexity driver' s visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss' classification
Caesar (1991, pp. 9-13) [1]						•	•									
Child *et al.* (1991b, pp. 53-54) [2]						•	•									
Cummings (1991, pp. 60-61) [2]						•	•									
Schäfer and Henning (1991, pp. 155-162) [1]						•	•									
Reiß (1992, p. 41) [1]						•						•				
Schmidt (1992, pp. 12-14) [1]		•				•	•									
Schulte (1992, pp. 84-86) [1]						•	•									
Rathnow (1993, pp. 7-10) [1]						•	•									
Reiß (1993a, pp. 3, 9) [1]		•				•	•									
Reiß (1993b, p. 54) [1]						•	•									
Rao and Young (1994, pp. 17-18) [2]						•				•						
Weber (1994, p. 24) [1]			•													
Fleck (1995, pp. 178-180) [1]		•				•	•									
Hadamitzky (1995, pp. 111-114) [1]						•				•						
Höge (1995, pp. 5-6, 16-17) [1]		•				•	•									
Kaiser (1995, pp. 100-102, 209) [1]						•	•									
Kestel (1995, pp. 18-29) [1]						•				•						
Kühl (1995, p. 7) [1]						•	•									
Schulte (1995, pp. 758-761) [1]						•	•									
Stark and Oman (1995, pp. 428-430) [2]				•	•											
Wildemann (1995, pp. 22-23) [1]						•	•									
Vizjak and Schiffers (1996, p. 9) [1]			•													
Raufeisen (1997, pp. 132-133) [1]						•						•				
Warnecke and Puhl (1997, pp. 359-362) [1]		•	•			•	•									
Adam (1998, pp. 33-40) [1]						•	•									
Berens and Schmitting (1998, p. 98) [1]		•				•	•									
Bliss (1998, pp. 147-148) [1]						•	•									•
Bohne (1998, pp. 58-63) [1]		•				•	•									
Calinescu *et al.* (1998, pp. 723-724) [2]						•					•					

Table 46: Results of literature analysis (Part B)

Language of literature source: [1] German [2] English	Content of literature sources based on literature’s analysis															
		RQ1	**RQ2 Approach for...**			**RQ3 Information about complexity drivers**										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver’ s identification	Complexity driver’ s operationalization	Complexity driver’ s visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss’ classification
Eversheim, Schenke and Warnke (1998, pp. 30-31) [1]						•	•									
Komorek (1998, p. 213) [1]						•		•								
Köster (1998, pp. 21-41) [1]						•	•									
Picot and Freudenberg (1998, pp. 70-71) [1]						•	•									
Rosemann (1998, pp. 60-61) [1]			•			•				•						
Wangenheim (1998b, pp. 30-33) [1]						•		•								
Wildemann (1998, pp. 47-52) [1]						•	•									
Benett (1999, pp. 12-14) [1]						•	•									
Flynn and Flynn (1999, pp. 1022-1024) [2]						•					•					
Heina (1999, pp. 10-17) [1]						•	•									
Piller and Waringer (1999, pp. 5-11) [1]		•				•	•									
Puhl (1999, pp. 31-33, 55-57, 69-71) [1]		•	•	•	•											
Raufeisen (1999, pp. 77-82, 201-211) [1]						•						•				
Reiners and Sasse (1999, pp. 222, 224) [1]						•	•									
Wildemann (1999a, pp. 64-66) [1]			•			•	•		•							
Wildemann (1999b, pp. 31-32) [1]		•				•	•									
Bliss (2000, pp. 4-7, 65-66, 163-169) [1]						•	•									•
Olbrich and Battenfeld (2000, pp. 1-6) [1]						•	•									
Westphal (2000, p. 19) [1]						•				•						
Franke and Firchau (2001, pp. 7-8) [1]						•	•									
Große Entrup (2001, pp. 11-18) [1]						•	•									
Schuh and Schwenk (2001, pp. 10-17) [1]						•	•									
Schwenk-Willi (2001, pp. 27-31) [1]		•				•	•									
Biersack (2002, pp. 52-54) [1]		•				•	•									
Fehling (2002, p. 26) [1]		•				•	•									
Deloitte (2003, p. 9) [2]						•									•	
Kim and Wilemon (2003, pp. 18-22) [2]						•		•								
Kirchhof (2003, pp. 39-41) [1]						•	•									•
Klabunde (2003, pp. 6-11) [1]						•	•									

Table 46: Results of literature analysis (Part C)

Language of literature source: [1] German [2] English	Content of literature sources based on literature's analysis															
		RQ1	**RQ2 Approach for...**			**RQ3 Information about complexity drivers**										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver' s identification	Complexity driver' s operationalization	Complexity driver' s visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss' classification
Meier, Hanenkamp and Bäcker (2003, pp. 10-11) [1]			•													
Pepels (2003, p. 551) [1]						•	•									
A.T. Kearney (2004, p. 3) [2]						•				•						
Dehnen (2004, pp. 32-35, 47) [1]		•				•		•								
Große-Heitmeyer and Wiendahl (2004, pp. 8-11) [1]						•	•									
Hanenkamp (2004, pp. 2-3, 62-67) [1]		•	•			•	•				•					
Hasenpusch, Moos and Schwellbach (2004, p. 135) [1]						•	•									•
Klaus (2004, pp. 364-367) [1]						•							•			
Keuper (2004, pp. 82-89) [1]						•	•									•
Klepsch (2004, pp. 7-9) [1]						•	•									
Payne and Payne (2004, pp. 116-119) [2]		•														
Perona and Miragliotta (2004, pp. 106-107, 110-114) [2]		•	•			•							•			
Purle (2004, pp. 109-117) [1]				•		•	•									
Rall and Dalhöfer (2004, pp. 626-627) [1]						•	•									
Wegehaupt (2004, pp. 38-39) [1]						•	•									
Blecker *et al.* (2005, pp. 59-60) [2]	•					•					•					
Blecker, Kersten and Meyer (2005, pp. 48-51) [2]						•							•			
Eichen *et al.* (2005, pp. 119-120) [1]						•	•									
Geimer (2005, pp. 40-43) [1]			•			•							•			
Greitemeyer and Ulrich (2005, pp. 2-3) [1]						•	•									
Jania (2004, pp. 7-8) [1]						•	•									
Krumm and Schopf (2005, p. 47) [1]			•													
Klinkner, Mayer and Thom (2005, p. 33) [1]						•				•						
Maschinenmarkt (2006) [1]						•			•		•					
Schuh (2005, pp. 8-19) [1]						•	•									
Schweiger (2005, pp. 40-41) [1]						•				•						
Wildemann (2005, pp. 34-35) [1]						•	•									

Table 46: Results of literature analysis (Part D)

Language of literature source: [1] German, [2] English

Authors	General statement about complexity drivers	RQ1: Definition of complexity drivers	RQ2 Approach for...: Complexity driver's identification	RQ2 Approach for...: Complexity driver's operationalization	RQ2 Approach for...: Complexity driver's visualization	RQ3 Information about complexity drivers: Overview about complexity drivers	RQ3 Fields: General in manufacturing companies	RQ3 Fields – Value Chain: Product Development	RQ3 Fields – Value Chain: Procurement/Purchasing	RQ3 Fields – Value Chain: Logistics	RQ3 Fields – Value Chain: Production	RQ3 Fields – Value Chain: Order Processing/Distribution/Sale	RQ3 Fields – Value Chain: Internal Supply Chain	RQ3 Fields – Value Chain: Remanufacturing	RQ3 Fields – Value Chain: General in Value Chain	RQ3: Using Bliss' classification
Anderson *et al.* (2006, p. 20) [2]						•						•				
Giannopoulos (2006, pp. 154-156) [2]		•	•			•		•								
Größler, Grübner and Milling (2006, pp. 256-257, 261-264) [2]			•	•		•	•									
Kaluza, Bliem and Winkler (2006, p. 3) [2]						•							•			
Kersten *et al.* (2006, pp. 326-328, 337) [2]						•				•						
Mansour (2006, pp. 60-61) [1]						•	•									
Piller (2006, pp. 54, 130-132) [1]						•	•									
Rudzio, Apitz and Denkena (2006, pp. 52-35) [1]		•				•	•									
Schuh, Sauer and Döring (2006, pp. 73-74) [1]					•											
Vickers and Kodarin (2006, p. 2) [2]			•			•							•			
Denk (2007, p. 19) [1]						•	•									
Hauptmann (2007, pp. 100-107) [1]						•			•		•					
Krause, Franke and Gausemeier (2007, pp. 16-19) [1]			•			•		•								
Kohagen (2007, p. 20) [1]			•													
Lübke (2007, pp. 179-184) [1]						•	•									
Marti (2007, pp. 14-17) [2]						•	•									•
Mayer (2007, pp. 23-31, 109) [1]						•	•			•						•
Meyer (2007, pp. 29-31, 101, 118-123) [1]		•		•	•	•	•			•						
Meyer and Brunner (2007, p. 32) [1]						•							•			
Ruppert (2007, pp. 68-70) [1]						•	•									
Steger, Amann and Maznevski (2007, pp. 4-5) [2]						•	•									
Waldthausen (2007, pp. 4-5) [1]						•						•				
Wildemann (2007a, p. 1723) [1]						•							•			
Aurich and Grzegorski (2008, p. 317) [1]						•	•									
Bick and Drexl-Wittbecker (2008, pp. 16, 29-31) [1]						•	•									
Curran, Elliger and Rüdiger (2008, p. 162) [1]						•	•									
Feldhusen and Gebhardt (2008, pp. 13-15) [1]						•	•									

Table 46: Results of literature analysis (Part E)

Language of literature source: [1] German [2] English	Content of literature sources based on literature's analysis															
		RQ1	**RQ2 Approach for...**			**RQ3 Information about complexity drivers**										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver's identification	Complexity driver's operationalization	Complexity driver's visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss' classification
Gabath (2008, pp. 35-36) [1]						•	•									
Greitemeyer, Meier and Ulrich (2008, pp. 37-39) [1]			•			•	•									
Scheiter, Scheel and Klink (2008, p. 2) [1]						•									•	
Schmidt, Wienholdt and Vorspel-Rüter (2008, p. 843) [1]						•					•					
Schubert (2008, pp. 134-136) [1]						•	•									
Asan (2009, pp. 36-37) [2]						•							•			
Ballmer (2009, p. 61) [1]			•													
Bozarth *et al.* (2009, pp. 81-82) [2]						•							•			
Dalhöfer (2009, pp. 25-26, 71-76) [1]				•		•	•									
Denk and Pfneissl (2009, pp. 21-24) [1]						•	•									
Dombrowski *et al.* (2009, p. 31) [1]						•	•									
Döpke, Kress and Kühl (2009, pp. 966-967) [1]						•	•									
F.A.Z. – Institut Management (2009, p. 13) [1]						•	•									
Gronau and Lindemann (2009, pp. 21-22) [1]						•					•					
Helfrich (2009, pp. 18-20, 37) [1]						•	•									
Lasch and Gießmann (2009a, pp. 200-202, 223-227) [1]			•	•	•	•	•			•						•
Lasch and Gießmann (2009b, pp. 97-98, 116-117) [1]			•	•	•	•	•									
Lindemann and Gronau (2009, p. 47) [1]						•					•					
Lindemann, Maurer and Braun (2009, p. 27) [2]						•	•									
Moos (2009, p. 54) [1]		•				•	•									
Nurcahya (2009, p. 29) [1]						•	•									
Schmid (2009, pp. 18-19) [1]						•	•									
Schmidt (2009, pp. 90-93) [1]						•	•									
Tenhiälä (2009, p. 1) [2]						•	•									
Wildemann (2009, pp. 364-369) [1]						•	•									
Abdelkafi, Blecker and Pero (2010, pp. 1407-1408) [2]						•							•			
Bayer (2010, pp. 9, 17) [1]			•			•	•									

Table 46: Results of literature analysis (Part F)

Language of literature source: [1] German, [2] English

Content of literature sources based on literature's analysis

Authors	General statement about complexity drivers	RQ1: Definition of complexity drivers	RQ2 Approach for…: Complexity driver's identification	RQ2 Approach for…: Complexity driver's operationalization	RQ2 Approach for…: Complexity driver's visualization	RQ3 Information about complexity drivers: Overview about complexity drivers	Fields: General in manufacturing companies	Value Chain: Product Development	Value Chain: Procurement/Purchasing	Value Chain: Logistics	Value Chain: Production	Value Chain: Order Processing/Distribution/Sale	Value Chain: Internal Supply Chain	Value Chain: Remanufacturing	Value Chain: General in Value Chain	Using Bliss' classification
Blockus (2010, pp. 16-22) [1]						•	•									
Buob (2010, pp. 15-22) [1]		•				•						•				
Gießmann (2010, pp. 36-38) [1]						•				•						•
Gießmann and Lasch (2010, pp. 155, 159-167) [1]		•				•			•							
Grussenmeyer and Blecker (2010, pp. 53-54) [2]						•		•								
Herrmann (2010, pp. 79-80) [1]						•	•									
Klug (2010, pp. 42-46) [1]						•				•						
Schließmann (2010, p. 59) [1]		•	•													
Schmitt, Vorspel-Rüter and Wienholdt (2010, pp. 843-844) [1]			•			•					•					
Schwandt and Franklin (2010, pp. 19-22) [2]						•	•									
Servatius (2010, p. 8) [1]						•	•									
Amann, Nedopil, Steger (2011, pp. 201-202) [2]						•	•									
Belz and Schmitz (2011, pp. 185-194) [1]						•						•				
Brosch *et al.* (2011a, pp. 856-857) [1]			•			•							•		•	
Brosch *et al.* (2011b, pp. 73-74) [1]				•	•	•							•		•	
Fässberg *et al.* (2011, pp. 4-5) [2]						•					•					
Gießmann and Lasch (2011, pp. 4-6) [1]						•				•						•
Gullander *et al.* (2011, p. 4) [2]						•					•					
Isik (2011, pp. 419-421) [2]						•							•			
Kersten (2011, pp. 16-17) [1]			•	•	•	•				•			•			
Lebedynska (2011, pp. 3-4) [1]						•					•					
Manuj and Sahin (2011, pp. 523-524) [2]						•							•			
Minhas, Lehmann and Berger (2011, p. 58) [2]						•					•					
Ortner, Hanusch and Schweiger (2011, p. 9) [1]						•			•							
Parry, Purchase and Mills (2011, pp. 68-72) [2]	•															
Schawel and Billing (2011, p. 111) [1]			•	•	•											
Schuh *et al.* (2011, pp. 118-119) [1]					•											
Scott, Lundgren and Thompson (2011, p. 170) [2]						•							•			

Table 46: Results of literature analysis (Part G)

Language of literature source: [1] German, [2] English

Content of literature sources based on literature's analysis. RQ1; RQ2 Approach for...; RQ3 Information about complexity drivers (Fields; Value Chain)

Authors	General statement about complexity drivers	RQ1: Definition of complexity drivers	RQ2: Complexity driver's identification	RQ2: Complexity driver's operationalization	RQ2: Complexity driver's visualization	RQ3: Overview about complexity drivers	RQ3 Fields: General in manufacturing companies	Value Chain: Product Development	Value Chain: Procurement/Purchasing	Value Chain: Logistics	Value Chain: Production	Value Chain: Order Processing/Distribution/Sale	Value Chain: Internal Supply Chain	Value Chain: Remanufacturing	Value Chain: General in Value Chain	RQ3: Using Bliss' classification
Serdarasan (2011, pp. 793-795) [2]		•				•							•			
Stich *et al.* (2011, p. 731) [1]						•					•					
Wildemann and Voigt (2011, pp. 44-52, 63-72) [1]						•	•									
Brosch *et al.* (2012, p. 127) [2]			•													
Collinson and Jay (2012, pp. 7-9, 30-32, 42-47) [2]			•			•	•									
Eigner, Anderl and Stark (2012, pp. 7-10) [1]						•		•								
ElMaraghy *et al.* (2012, pp. 793-794, 798) [2]						•		•			•					
Gerschberger *et al.* (2012, pp. 1015-1016) [2]		•														
Haumann *et al.* (2012, pp. 107-111) [2]			•	•	•	•								•		
Hering *et al.* (2012, p. 11) [1]						•						•				
Kersten, Lammers and Skirde (2012, pp. 21-32) [1]			•	•	•	•						•				
Klagge and Blank (2012, pp. 6-7) [1]						•							•			
Lammers (2012, pp. 31-35, 100-103) [1]		•		•	•	•						•				•
Schömann (2012, pp. 135-138) [1]						•		•								•
Steinhilper *et al.* (2012, pp. 361-364) [1]			•	•	•	•								•		
Wildemann (2012, p. 24) [1]						•	•									
Zhang and Yang (2012, pp. 231-232) [2]						•		•								
Aelker, Bauernhansl and Ehm (2013, pp. 81-82) [2]				•	•	•							•			
Binckebanck and Lange (2013, pp. 99-103) [1]						•						•				
Borowski and Henning (2013, pp. 30-32) [1]						•					•					
Brandenburg (2013, p. 55) [2]						•							•			
Gille (2013, pp. 98-99) [1]						•	•									
Götzfried (2013, pp. 35-38, 67-68) [2]		•				•	•									•
Jäger *et al.* (2013, p. 341) [1]						•	•									
Kolbusa (2013a, pp. 85-86) [1]						•	•									
Kolbusa (2013b, pp. 89-92) [2]						•	•									
Leeuw, Grotenhuis and Goor (2013, pp. 960-970) [2]		•	•			•							•			

Table 46: Results of literature analysis (Part H)

Language of literature source: [1] German [2] English	Content of literature sources based on literature's analysis															
		RQ1	**RQ2 Approach for...**			**RQ3 Information about complexity drivers**										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver's identification	Complexity driver's operationalization	Complexity driver's visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss' classification
Schuh, Krumm and Amann (2013, pp. 30, 40-41) [1]						•	•									
Seifert *et al.* (2013, pp. 648-652) [2]			•	•	•	•								•		
Serdarasan (2013, pp. 534-535) [2]			•			•							•			
Brandenburg *et al.* (2014, p. 6) [2]						•							•			
Budde and Golovatchev (2014, p. 602) [1]						•		•								
Butzer *et al.* (2014, pp. 366-369) [2]						•								•		
Ehrlenspiel *et al.* (2014, p. 297) [1]						•					•					
Grimm, Schuller and Wilhelmer (2014, pp. 91-93) [1]						•	•									•
Henning and Borowski (2014, p. 59) [1]						•					•					
Huber (2014, pp. 13-15) [1]						•									•	
Jensen, Bekdik and Thuesen (2014, p. 541) [2]						•		•								
Krah (2014) [1]						•	•									
Link (2014, p. 65) [1]						•	•									
Lucae, Rebentisch and Oehmen (2014, pp. 658-659) [2]	•					•		•								
Mahmood, Rosdi and Muhamed (2014, p. 1851) [2]	•															
Sauter (2014, p. 5) [1]						•	•									
Schoeneberg (2014a, pp. 16-19) [1]						•	•									•
Schöttl *et al.* (2014, pp. 255, 259-260) [2]						•					•					
Schuh *et al.* (2014a, pp. 314-315) [1]					•											
Schuh *et al.* (2014b, p. 184) [1]						•			•							
Schuh *et al.* (2014c, p. 347) [2]						•					•					
Stauder *et al.* (2014, p. 128) [2]						•					•					
Thiebes and Plankert (2014, pp. 171-172) [1]						•		•								
Wassmus (2014, pp. 69-71) [1]						•						•				
Zimmermann and Fabisch (2014, p. 252) [1]						•				•						
Bode and Wagner (2015, p. 216) [2]						•							•			
Bosch-Rekveldt *et al.* (2015, pp. 1084-1086, 1099) [2]			•			•		•								

Table 46: Results of literature analysis (Part I)

Language of literature source: [1] German [2] English	Content of literature sources based on literature's analysis															
		RQ1	RQ2 Approach for...			RQ3 Information about complexity drivers										
							Fields									
								Value Chain								
Authors	General statement about complexity drivers	Definition of complexity drivers	Complexity driver’s identification	Complexity driver’s operationalization	Complexity driver’s visualization	Overview about complexity drivers	General in manufacturing companies	Product Development	Procurement/Purchasing	Logistics	Production	Order Processing/Distribution/Sale	Internal Supply Chain	Remanufacturing	General in Value Chain	Using Bliss’ classification
Bretzke (2015, p. 42) [1]						•				•						
Christ (2015, p. 58) [1]		•														
Claeys *et al.* (2015, p. 925) [2]						•					•					
Ehrenmann (2015, pp. 15-21) [1]	•															
Krizanits (2015, pp. 44-47) [1]	•				•											
Oyama, Learmonth and Chao (2015, p. 5) [1]						•		•								
Reuter, Prote and Stöwer (2015, p. 9) [1]						•					•					
Schmidt (2015, pp. 1-2) [1]						•	•									
Schmitz (2015, p. 66) [1]						•						•				
Schott, Horstmann and Bodendorf (2015, pp. 33-36) [2]			•													
Schuh, Gartzen and Wagner (2015, pp. 2, 4) [2]		•				•					•					
Sun and Rose (2015, pp. 1211-1215) [2]	•															
Wallner, Brunner and Zsifkovits (2015, pp. 7-13) [2]						•							•			
Wulf, Redlich and Wulfsberg (2015, p. 109) [1]						•									•	
Total Amount of German Sources: 169	7	31	36	17	18	212	108	17	6	18	25	13	26	4	6	15
Amount of English Sources: 66								Total Value Chain: 115								

Table 47: Overview about complexity driver categories and their specific drivers (Part A)

Origin	Complexity driver category and their specific drivers		
External complexity	**Society complexity**		**Σ: 25**
	• Social framework	• Social change	• Value change
	• Social behavior	• Cultural framework	• Political framework conditions
	• Social requirements	• Cultural differences	• Standards and regulations
	• Change of company's environment	• Dynamic in company's environment	• Language and cultural differences
	• Environmental awareness	• Legal factors	• Internet
	• Economical framework conditions	• Economical networking	• Uncertainty in company's environment
	• Country-specific requirements	• Geographical factors	• Cultural factors (language, working hours, habit, working method, education)
	• Ecological conditions/factors	• Exponential populations growth	
	• Turbulences in company's environment	• Interdependencies between different environmental factors	
	Market complexity		**Σ: 61**
	General market-related complexity drivers		**Σ: 18**
	• Market framework conditions	• Number of different markets	• Development of new markets
	• Market's requirements	• Market's structure	• Market's change
	• Market's size	• Market's dynamics	• Market's diversity
	• Market's uncertainty	• Market's fluctuations	• Market's turbulences
	• Saturation of the market	• Market's internationalization	• Market's deregulations
	• Market's extensiveness	• Market's globalization	• Market's protectionism
	Demand-related complexity drivers		**Σ: 7**
	• Globalization of the demand	• Number of customers	• Variety of customer demands
	• Individuality of customer demands	• Heterogeneity of customer demands	• Demand uncertainty
	• Fluctuation in demand		
	Competitive-related complexity drivers		**Σ: 8**
	• Number of competitors	• Strength of competitors	• Increasing international competition
	• Competitive demands	• Competitive differentiation	• Competitive dynamics
	• Competitive activities	• Competitive pressure	
	Supply-related complexity drivers		**Σ: 19**
	• Number of suppliers	• Variety of suppliers	• Supplier's structure
	• Supplier's reliability	• Supplier's qualification	• Supplier's network
	• Supplier's change	• Supplier's relationship	• Number of supplied objects
	• Heterogeneity of supplied objects	• Dynamics in the buying market	• Source of supply
	• Supply strategy	• Globalization of the supply chain	• Number of deliveries
	• Number of part-deliveries	• Number of different delivered parts	• Uncertainty of delivery dates
	• Uncertainty of delivery quality		
	Technological-related complexity drivers (external)		**Σ: 9**
	• Technological progress	• Technological change	• Different technological standards
	• Technological innovations	• Technological intensity	• Technological dynamics
	• New technologies and materials	• Combination of different technologies	• Technology integration

Table 47: Overview about complexity driver categories and their specific drivers (Part B)

Origin	Complexity driver category and their specific drivers		
Internal correlated complexity	**Target complexity**		**Σ: 7**
	• Amount of different targets	• Target's diversity	• Dynamics of target adaption
	• Maturity of target achievement	• Missing target's comparison	• Conflict between different targets
	• Ambiguity of targets		
	Customer complexity		**Σ: 10**
	• Customer complexity general	• Customer's structure	• Number of customers
	• Customer's diversity	• Customer group's heterogeneity	• Customer's requirements
	• Customer's participation	• Long-term customer loyalty	• Diversity of customers relations
	• Degree of customer's dependency		
	Product & Product portfolio complexity		**Σ: 43**
	• Product variety	• Availability of raw materials	• Modularity of parts and modules
	• Product range's structure	• Product diversity	• Variety of applied materials
	• Product portfolio's size	• Number of product modifications	• Product range/portfolio
	• Country-specific product portfolio	• Product portfolio's structure	• Number of exotic product variants
	• Dynamics in product program change	• Number of different product lines	• Customer-specific product portfolio
	• Product structure/design	• Deficits in coordination between the product development, marketing and sales department during the product portfolio definition process	• Number of product launches
	• Product size		• Product concept
	• Product performance		• Product geometry
	• Product quality	• Product type	• Product function
	• Conflicts between different standards	• Product weight	• Engineer standards
	• Product technology	• Product requirements	• Product life cycle
	• Component type	• Quality standards	• Product innovation
	• Variety of parts and modules	• Product uncertainty	• Number of parts and modules
	• Number of applied materials	• Number of product technologies	• Properties of the applied materials
	• Number of raw materials in a product	• Component variety	• Heterogeneity of applied materials
	Technological-related complexity (internal)		**Σ: 15**
	• Technology complexity general	• Technology change/Innovations	• New technologies
	• Technological requirements	• Number of different technologies	• Technology/Innovation compulsion
	• Availability of technologies	• Technological uncertainty	• Technology life cycle
	• Effort for technology's innovations	• Type of data medium	• Size of data medium
	• Type of interfaces	• Amount of interfaces	• Criteria of hardware/software tests
	Product development complexity		**Σ: 8**
	• Development complexity general	• Development program's complexity	• Product development's dynamic
	• Product development's length	• Number of development partners	• Product development's procedure
	• Applied methods or instruments	• Product development's depth	
	Supply process complexity		**Σ: 7**
	• Supply process complexity general	• Supply strategy	• Number of supply goods
	• Delivery of stocks	• Order's heterogeneity	• Demand's fluctuation
	• Forecast uncertainty		
	Service complexity		**Σ: 3**
	• Service complexity general	• Service variety	• Service concept
	Remanufacturing complexity		**Σ: 3**
	• Remanufacturing complexity general	• Remanufacturing process	• Product structure

Table 47: Overview about complexity driver categories and their specific drivers (Part C)

Origin	Complexity driver category and their specific drivers		
Internal autonomous complexity	**Organizational complexity**		**∑: 105**
	• Organization (general)	• Organization's/Company's size	• Company's legal status
	• Business segment/industrial sector	• Business culture	• Number of subsidiaries
	• Company's locations	• Globalization of company's locations	• Company's business management
	• Company's strategy	• Changes in company's strategy	• Multibrand strategy
	• Company's specialization	• Decision-making process (general)	• Length of decision-making process
	• Number of contractual partners	• Confidence in contractual partners	• Number of different time zones
	• Number of different nationalities in the company	• Number of different languages in the company	• Handling of risks, uncertainty and incidence
	• Number of joint-ventures	• Structures of joint-ventures	• Cash flow dynamics
	• Number of different financial sources	• Bureaucracy	• Business relationship
	• Length of business relationship	• Avarice for money	• Data security
	• Multiplicity of company's activities	• Variety of company's activities	• Coordination deficits between different departments
	• Pricing policy	• Coordination effort	
	• Number of tasks	• Task's variety	• Task coordination
	• Dependencies between different tasks	• Degree of centralization	• Degree of labor division
	• Number of cooperation partners	• Cooperation intensity	• Degree of cooperation
	• Organization's structure	• Organization structure's variety	• Organization structure's diversity
	• Deficits in organization structure	• Reorganization of organization's structure	• Dependencies between organizational units
	• Number of organizational units	• Number of organizational levels	• Degree of centralization
	• Variety of hierarchical levels	• Egoism of different departments	• Number of supervisory authorities
	• Employees (general)	• Number of employees	• Requirement profile and expectations
	• Employee's qualification	• Employee's language	• Employees' culture
	• Employee's experience	• Employee's behavior	• Employee's turnover
	• Employee's workload	• Working atmosphere	• Uncertainty related to an employee
	• Employee's absence	• Personnel decision	• Labor division and specialization
	• Employee's striving for power	• Employee's (negative) emotions	• Employee's motivation
	• Shifting of responsibilities	• Lack of professional competence	• Lack of social competence
	• Number of interfaces between other employees	• Separation of task, responsibilities and experience	• Lack of motivation and identification with company's goals
	• Company's management	• Management's responsibility	• Management's philosophy
	• Management's behavior	• Missing assignment of responsibilities	• Unclear assignment of responsibilities
	• Value chain (general)	• Value chain structure	• Value chain's length
	• Value chain's geographical position	• Added value process	• Added value network
	• Depth of added value	• Number of steps in value chain	• Number of non-value added processes
	• Lack of transparency (general)	• Lack of cost transparency	• Lack of cost understanding
	• Lack in consistency of activities	• Missing readiness for change	• Subjective evaluation of situations
	• Lack in complexity management processes	• Lack in complexity management instruments	• Weaknesses in transformation of decisions
	• Deficits in methods		
	Process complexity		**∑: 25**
	• Process complexity (general)	• Number of processes	• Variety of processes
	• Process type	• Process structure	• Number of process steps
	• Length of process	• Process automatization	• Process fragmentation
	• Process planning	• Process innovations	• Process dynamic
	• Process orientation	• Process optimization	• Special processes
	• Process uncertainty	• Process stability	• Process connectivity
	• Process standardization	• Number of process interfaces	• Number of internal interfaces
	• Number of external interfaces	• Interfaces' design	• Interfaces' heterogeneity
	• Concentration of process interfaces		

Table 47: Overview about complexity driver categories and their specific drivers (Part D)

Origin	Complexity driver category and their specific drivers		
Internal autonomous complexity	**Production complexity**		**∑: 39**
	• Production (general)	• Production structure	• Production organization
	• Production program	• Production program's structure	• Production program's volume
	• Production program's heterogeneity	• Production program's planning	• Production program's network
	• Number of production locations	• Production location's structure	• Geographical position of production locations
	• Size of production area	• Production system	
	• Production system's variety	• Size of production system	• Production organization
	• Production strategy	• Production type	• Number of production processes
	• Number of production interfaces	• Design of production interfaces	• Number of production steps
	• Variety of production steps	• Manufacturing technology	• Manufacturing performance
	• Number of work stations	• Uncertainties in production methods	• Capacity uncertainty
	• Machine maintenance	• Breakdown of production machines	• Production control system
	• Type of work	• Lead time	• Queue time
	• Degree of production automatization	• Production scheduling	• Material flow
	• Material flow's dynamic		
	Planning, control and information complexity		**∑: 41**
	• Planning content	• Scheduling	• Strategic planning
	• Lack in strategic planning	• Number of internal projects	• Time pressure in project planning
	• Project time	• Project's control	• Number of information
	• Information variety	• Information asynchrony	• Documentation
	• Number of controlling authorities	• Control systems (general)	• Control processes
	• Control instruments	• Control demand's rate	• Control demand's level of detail
	• Information and communication complexity (general)	• Information and communication technologies	• Information and communication network • Variety of information systems
	• Information systems	• Number of information systems	• Communication structure
	• Communication systems	• Number of communication systems	• Information deficits
	• Information flow	• Information asymmetry	• Lack in information systems
	• Information and data overload	• Information medium	• Data security
	• Lack in communication systems	• Company's communication behavior	• Applied software
	• Organization information technology systems	• Structure of information technology systems	• Development of information technology systems
	• Software's changing		
	Resource complexity		**∑: 9**
	• Resource complexity (general)	• Resource's type	• Number of different resources
	• Resource's availability	• Resource's shortage	• Application of resources
	• Sequence of resource's application	• Restricted flexibility of resources	• Resource's stocks
	Logistics complexity		**∑: 17**
	• Logistic complexity (general)	• Logistic principle	• Logistic structure
	• Logistic chain	• Logistic strategy	• Logistic process
	• Heterogeneity of logistic process	• Logistic network	• Logistic outsourcing
	• Supply chain general	• Supply chain structure	• Supply chain size
	• Supply chain process	• Supply chain organization	• Supply chain bottleneck
	• Number of supply chain partners	• Supply chain synchronization	

Table 47: Overview about complexity driver categories and their specific drivers (Part E)

Origin	Complexity driver category and their specific drivers		
	Sales & Distribution complexity		**∑: 40**
Internal autonomous complexity	• Distribution system (general)	• Innovations in distribution system	• Distribution system's output
	• Stock level in distribution system	• Deficits in distribution system	• Distribution process
	• Distribution network	• Number of distribution partners	• Number of distribution center
	• Number of distribution stages	• Distribution channel	• Number of distribution channels
	• Distribution innovations	• Transportation route	• Transportation source
	• Restriction in storage spaces	• Number of pick stations	• Distribution deadlines
	• Order processing (general)	• Order processing's variety	• Order processing's individualization
	• Number of different orders	• Order structure	• Order's size
	• Order's heterogeneity	• Handling time	• Sale's structure
	• Sales concept	• Sales pressure	• Sale's region
	• Definition of customer groups	• Customer's loyalty	• Treaty structure
	• Number of sale tasks	• Diversity of sale tasks	• Sale's significance in the company
	• Sale's cooperation with other departments	• Marketing strategy	• Marketing concepts
	• Marketing instruments		
	General complexity driver		**∑: 28**
General complexity	• Variety	• Diversity	• Dynamics
	• Uncertainty	• Stability	• Instability
	• Perception	• Time	• Costs
	• Cost effectiveness	• Quality	• Flexibility
	• Transparency	• Connectivity	• Dependency
	• Interaction	• Interdependency	• Degree of change
	• Inconsistency	• Discontinuity	• Lack of structures
	• Speed	• Amount of units and elements	• Amount of actions and relationships
	• Amount of actions between units	• Amount of relationships between units	• Element's system affiliation
	• Ambiguity		

Table 48: General Framework of literature collection, focused on empirical research in the field complexity management

Focus	Database	Search terms	Date	Results
General in manufacturing companies	EBSCOhost	(Komplexität N10 Management) AND (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/04/23	3
		(complexity N10 management) AND (study OR survey OR empir* OR questioning OR interview)	17/04/23	750
	Emerald	"Komplexität?" AND (Studie OR Untersuchung OR Empir? OR Befrag? OR Interview)	17/03/24	4
		("complexity management" OR "management of complexity") AND (study OR survey OR empir? OR questioning OR interview)	17/03/30	148
	GENIOS/ WISO	Komplexität* ndj5 (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/03/02	600
		complexity ndj5 (study OR survey OR empir* OR questioning OR interview)	17/03/04	790
	Google Scholar	"Komplexität*" AND ("Studie" OR "Untersuchung" OR "Empir*" OR "Befrag*" OR "Interview")	17/03/09	4,200
		"complexity" AND ("study" OR "survey" OR "empir*" OR "questioning" OR "interview")	17/03/12	14,910
	IEEE Xplore	Komplexität* NEAR/2 (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/03/18	4
		complexity NEAR/2 (study OR survey OR empir* OR questioning OR interview)	17/03/16	1,232
	JSTOR	("Komplexität Management"~5) AND (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/04/17	27
		("complexity management"~5) AND (study OR survey OR empir* OR questioning OR interview)	17/04/23	2,462
	ScienceDirect	Komplexität* AND (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/03/19	112
		complexity AND (study OR survey OR empir* OR questioning OR interview)	17/03/22	282
	SpringerLink	(Komplexität NEAR/5 Management) AND (Studie OR Untersuchung OR Empir* OR Befrag* OR Interview)	17/04/06	728
		(complexity NEAR/5 management) AND (study OR survey OR empir* OR questioning OR interview)	17/04/12	447
			Total:	**26,699**

Table 49: Intercorrelations between complexity drivers (Part A)

Complexity drivers	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Value change & value awareness	**1**	1																															
Environmental awareness in population	**2**	.59**	1																														
Ecological conditions/factors	**3**	.42**	.78**	1																													
Political framework conditions	**4**	.25**	.37**	.42**	1																												
Legal factors	**5**	.28**	.32**	.32**	.36**	1																											
Market's infrastructure	**6**	.18**	.26**	.27**	.32**	.28**	1																										
Market's economic factors	**7**	.15**	.14*	.21**	.18**	.12*	.32**	1																									
Variety of customer requirements	**8**	.05	.10	.13*	.02	.10	.15*	.36**	1																								
Individuality of customer demands	**9**	.12*	.10	.17**	-.05	.03	.16**	.33**	.64**	1																							
Demand's dynamics	**10**	.23**	.25**	.21**	.13*	.04	.24**	.35**	.35**	.50**	1																						
Number & strength of competitors	**11**	-.01	.14*	.19**	.14*	-.03	.14*	.26**	.13*	.18**	.31**	1																					
Market's change	**12**	.13*	.19**	.25**	.19**	.14*	.23**	.31**	.28**	.28**	.35**	.42**	1																				
Competitor's dynamics	**13**	.14*	.17**	.20**	.17**	.09	.20**	.29**	.23**	.22**	.32**	.55**	.43**	1																			
Market's globalization	**14**	.07	.14*	.15*	.20**	.07	.30**	.30**	.15*	.13*	.22**	.34**	.54**	.42**	1																		
Technological progress	**15**	.03	.06	.07	.12*	.17**	.27**	.24**	.21**	.14*	.17**	.27**	.37**	.43**	.41**	1																	
Technological innovations & availability	**16**	.08	.06	.07	.09	.13*	.24**	.25**	.17**	.15*	.18**	.24**	.29**	.41**	.31**	.73**	1																
Variety of supplied goods	**17**	.17**	.16**	.17**	.19**	.18**	.22**	.22**	.08	.05	.22**	.12*	.22**	.32**	.17**	.19**	.27**	1															
Amount of suppliers	**18**	.08	.12*	.09	.23**	.14*	.18**	.13*	.05	.02	.19**	.14*	.18**	.27**	.24**	.21**	.23**	.67**	1														
Supply strategy or concept	**19**	.06	.12*	.10	.16**	.10	.20**	.11	.05	.05	.15*	.12*	.21**	.24**	.21**	.19**	.25**	.53**	.67**	1													
Quality uncertainty of delivered goods	**20**	.12*	.11	.08	.07	.13*	.19**	.16**	.05	.03	.13*	.07	.13*	.17**	.20**	.23**	.18**	.38**	.40*	.53**	1												
Uncertainty of delivery date	**21**	.08	.10	.07	.09	.06	.23**	.14*	.10	.05	.16**	.07	.17**	.17**	.21**	.20**	.13*	.33**	.39**	.47**	.73**	1											
Amount of different targets	**22**	.23**	.15**	.11	.06	.19**	.18**	.04	.12*	.14*	.21**	.13*	.10	.16**	.10	.18**	.17**	.13*	.03	.13*	.14*	.13*	1										
Business objective's change frequency	**23**	.21**	.13*	.09	.10	.24**	.17**	.01	.06	.01	.08	.08	.09	.14*	.06	.21**	.21**	.15**	.10	.21**	.15**	.17**	.61**	1									
Business objective's time pattern	**24**	.06	.10	.80	-.01	.15*	.13*	.12*	.14*	.06	.01	.08	.17**	.25**	.14*	.24**	.20**	.18**	.14*	.17**	.10	.10	.41**	.50**	1								
Customer's amount	**25**	.02	.05	.06	.04	.09	.12*	.14*	.32**	.25**	.28**	.18**	.26**	.28**	.24**	.33**	.22**	.20**	.21**	.24**	.20**	.18**	.16**	.14*	.18**	1							
Customer structure	**26**	.03	.03	.06	.06	.08	.08	.18**	.37**	.26**	.28**	.14*	.27**	.27**	.27**	.28**	.17**	.18**	.22**	.19**	.15**	.15**	.13*	.06	.12*	.75**	1						
Customer's participation	**27**	-.05	.03	.11	.12*	.01	.13*	.14*	.24**	.21**	.15*	.10	.20**	.22**	.24**	.23**	.17**	.20**	.22**	.16**	.12*	.18**	-.06	-.03	.07	.43**	.46**	1					
Product variety	**28**	.13*	.09	.14*	.14*	.04	.06	.19**	.24**	.23**	.25**	.17**	.19**	.33**	.19**	.20**	.18**	.28**	.22**	.14*	.07	.11	.18**	.14*	.11	.43**	.47**	.34**	1				
Product range/Portfolio	**29**	.03	.03	.13*	.17**	.04	.03	.08	.19**	.20**	.19**	.16**	.21**	.28**	.16**	.18**	.14*	.24**	.22**	.16**	.09	.07	.18**	.14*	.13*	.37**	.45**	.38**	.68**	1			
Product portfolio change frequency	**30**	.13*	.16**	.11	.15*	.15*	.18**	.18**	.13*	.05	.12*	.12*	.18**	.38**	.20**	.26**	.26**	.34**	.31**	.22**	.17**	.19**	.14*	.28**	.27**	.25**	.24**	.23**	.43**	.39**	1		
New product launch's frequency	**31**	.22**	.23**	.22**	.12*	.21**	.21**	.14*	.19**	.17**	.19**	.14*	.20**	.36**	.17**	.25**	.21**	.30**	.24**	.26**	.19**	.21**	.28**	.27**	.31**	.25**	.23**	.16**	.39**	.32**	.64**	1	
Product life cycle length	**32**	.09	.04	.05	.12*	.12*	.21**	.09	.11	.06	.12*	.04	.18**	.22**	.22**	.23**	.18**	.10	.10	.14*	.17**	.18**	.10	.19**	.24**	.26**	.23**	.15**	.29**	.25**	.32**	.39**	1

Note: ** = significant at the 0.01 level
* = significant at the 0.05 level
N = 295 companies

Explanation for intercorrelations: very strong correlations; strong correlations; medium correlations

Table 49: Intercorrelations between complexity drivers (Part B)

Complexity drivers	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Product structure/design	**33**	.03	.12*	.15*	.13*	.13*	.18**	.12*	.16**	.03	.10	.16**	.23**	.28**	.18**	.15**	.12*	.27**	.30**	.26**	.22**	.18**	.16**	.17**	.25**	.21**	.21**	.29**	.26**	.31**	.36**	.40**	.42**
Variety of parts and modules	**34**	.15**	.14*	.16**	.16**	.16**	.13*	.10	.17**	.07	.16**	.08	.18**	.20**	.16**	.22**	.20**	.32**	.35**	.29**	.21**	.22**	.12*	.20**	.20**	.22**	.22**	.23**	.30**	.33**	.35**	.33**	.40**
Variety of the applied materials	**35**	.17**	.18**	.24**	.11	.18**	.20**	.11	.11	.06	.13*	.09	.08	.20**	.14*	.20**	.20**	.37**	.39**	.32**	.34**	.27**	.18**	.21**	.19**	.22**	.18**	.16**	.23**	.20**	.26**	.32**	.33**
Variance in product design	**36**	.13*	.13*	.08	.05	.06	.22**	.11*	.18**	.21**	.14*	.09	.15*	.20**	.16**	.21**	.23**	.26**	.27**	.26**	.17**	.16**	.19**	.20**	.23**	.15**	.14*	.15*	.21**	.13*	.29**	.39**	.28**
Availability of materials or components	**37**	.13*	.15**	.14*	.07	.15*	.22**	.13*	.09	.01	.10	.03	.12*	.11	.09	.22**	.20**	.29**	.32**	.27**	.37**	.35**	.13*	.13*	.21**	.15*	.04	.16**	.11	.13*	.15**	.21**	.30**
Properties of modules and materials	**38**	.17**	.25**	.20**	.14*	.15**	.23**	.13*	-.10	-.04	.06	.02	.07	.12*	.14*	.17**	.12*	.22**	.30**	.27**	.44**	.31**	.15*	.08	.16**	.14*	.08	.19**	.07	.08	.16**	.26**	.26**
Product's degree of innovation	**39**	.24**	.29**	.21**	.13*	.19**	.23**	.17**	.18**	.06	.09	.15*	.14*	.22**	.20**	.28**	.28**	.16**	.17**	.15**	.18**	.18**	.27**	.33**	.29**	.19**	.17**	.10	.21**	.13*	.30**	.39**	.31**
Product life cycle length	**40**	.13*	.09	.04	.07	.14*	.16**	.21**	.23**	.15**	.17**	.09	.22**	.25**	.19**	.30**	.26**	.18**	.16**	.17**	.22**	.16**	.16**	.15*	.21**	.25**	.23**	.21**	.32**	.21**	.25**	.33**	.58**
Technology change/innovation	**41**	.09	.16**	.10	.07	.13*	.25**	.22**	.20**	.12*	.12*	.13*	.26**	.24**	.26**	.42**	.41**	.19**	.21**	.26**	.28**	.23**	.23**	.18**	.26**	.22**	.20**	.16**	.21**	.18**	.32**	.35**	.33**
Number of different applied technologies	**42**	.08	.17**	.17**	.19**	.27**	.26**	.20**	.17**	.09	.12*	.08	.26**	.16**	.27**	.39**	.37**	.26**	.28**	.31**	.28**	.20**	.21**	.23**	.23**	.21**	.16**	.22**	.22**	.22**	.36**	.41**	.35**
Technology's complicacy	**43**	.07	.17*	.16**	.16**	.16**	.26**	.19**	.15**	.08	.17**	.13*	.23**	.20**	.27**	.39**	.32**	.20**	.24**	.32**	.22**	.20**	.18**	.14*	.26**	.22**	.20**	.23**	.23**	.16**	.29**	.37**	.33**
Technology's combination	**44**	.10	.18**	.20**	.21**	.20**	.27**	.15**	.15*	.04	.11	.09	.24**	.17**	.26**	.34**	.28**	.20**	.19**	.24**	.18**	.20**	.20**	.16**	.18**	.20**	.15**	.17**	.17**	.17**	.30**	.35**	.30**
Technology life cycle length	**45**	.04	.09	.11	.18**	.13*	.23**	.07	.20**	.09	.13*	.06	.26**	.22**	.23**	.33**	.29**	.21**	.16**	.25**	.18**	.15*	.20**	.19**	.21**	.23**	.23**	.19**	.21**	.18**	.32**	.35**	.46**
Product software	**46**	.07	.06	.03	.13*	.12*	.18**	.12*	.09	.04	.17**	.07	.22**	.22**	.22**	.30**	.25**	.24**	.19**	.26**	.17**	.15**	.14*	.16**	.09	.18**	.20**	.24**	.25**	.24**	.28**	.27**	.24**
Data processing system	**47**	.09	.11	.10	.16**	.15**	.20**	.19**	.040	-.01	.13*	.04	.26**	.17**	.28**	.30**	.20**	.23**	.23**	.27**	.24**	.24**	.11	.16**	.17**	.12*	.16**	.20**	.17**	.19**	.26**	.23**	.18**
Vertical range of manufacture	**48**	.11	.16**	.13*	.06	.13*	.15**	.09	.20**	.15*	.16**	.05	.18**	.09	.21**	.13*	.10	.09	.12*	.14*	.16**	.20**	.24**	.04	.17**	.20**	.14*	.20**	.22**	.21**	.15*	.19**	.20**
Production system	**49**	.03	.13*	.15*	.07	.15**	.15**	.13*	.19**	.12*	.12*	.06	.18**	.08	.25**	.21**	.17**	.13*	.16**	.18**	.19**	.20**	.20**	.05	.19**	.24**	.22**	.27**	.26**	.24**	.18**	.25**	.19**
Variety of processes	**50**	.11	.14*	.16**	.14*	.19**	.18**	.21**	.23**	.14*	.16**	.12*	.22**	.14*	.26**	.23**	.12*	.11	.16**	.19**	.18**	.17**	.28**	.17**	.23**	.22**	.24**	.15*	.26**	.25**	.19**	.20**	.26**
Amount of process interfaces	**51**	.12*	.20**	.20**	.20**	.19**	.21**	.22**	.25**	.16**	.18**	.13*	.19**	.13*	.28**	.25**	.17**	.12*	.15*	.20**	.09	.10	.30**	.21**	.23**	.23**	.24**	.15**	.28**	.27**	.20**	.24**	.24**
Process degree of cross-linking	**52**	.15**	.16**	.16**	.19**	.20**	.19**	.24**	.19**	.14*	.25**	.17**	.26**	.17**	.29**	.29**	.19**	.12*	.13*	.24**	.12*	.11	.30**	.20**	.23**	.18**	.18**	.08	.20**	.19**	.17**	.27**	.25**
Process standardization	**53**	.12*	.19**	.25**	.20**	.21**	.11	.12*	.19**	.08	.15**	.10	.23**	.14*	.20**	.22**	.13*	.10	.12*	.19**	.15**	.14*	.19**	.14*	.19**	.24**	.21**	.14*	.19**	.20**	.13*	.23**	.18**
Information flow's variety	**54**	.12*	.14*	.14*	.21**	.17**	.20**	.17**	.16**	.11	.20**	.17**	.24**	.15*	.21**	.30**	.18**	.21**	.18**	.33**	.15*	.16**	.23**	.24**	.21**	.20**	.19**	.14*	.20**	.19**	.19**	.27**	.19**
Information flow's dynamics	**55**	.16**	.16**	.14*	.23**	.18**	.26**	.17**	.18**	.12*	.20**	.13*	.24**	.19**	.19**	.29**	.19**	.25**	.22**	.33**	.17**	.17**	.23**	.26**	.26**	.22**	.20**	.16**	.21**	.21**	.26**	.33**	.20**
Amount of hierarchical levels	**56**	.20**	.22**	.17**	.15*	.20**	.24**	.18**	.09	.03	.16**	.21**	.29**	.18**	.24**	.20**	.10	.20**	.24**	.29**	.23**	.25**	.29**	.34**	.27**	.23**	.17**	.19**	.21**	.19**	.29**	.25**	.25**
Organization's/Company's size	**57**	.23**	.21**	.22**	.18**	.20**	.26**	.18**	.08	.04	.18**	.20**	.30**	.20**	.27**	.23**	.16**	.15**	.17**	.23**	.17**	.20**	.31**	.34**	.31**	.22**	.18**	.14*	.25**	.22**	.30**	.29**	.33**
Degree of centralization	**58**	.22**	.14*	.11	.13*	.22**	.14*	.14*	.11	.06	.18**	.11	.26**	.08	.20**	.15*	.03	.06	.05	.12*	.20**	.21**	.24**	.30**	.20**	.29**	.25**	.16**	.20**	.23**	.21**	.28**	.29**
Amount of simultaneous projects	**59**	.08	.11	.11	.15*	.24**	.14*	.09	.15**	.06	.09	.17**	.16**	.14*	.10	.17**	.14*	.08	.14*	.21**	.11	.12*	.38**	.34**	.32**	.24**	.20**	.02	.17**	.18**	.18**	.27**	.19**
Amount of simultaneous processes	**60**	.10	.10	.10	.15**	.24**	.19**	.16**	.18**	.11	.14*	.14*	.20**	.11	.13*	.23**	.18**	.16**	.22**	.23**	.15*	.17**	.38**	.32**	.31**	.23**	.21**	.04	.19**	.17**	.21**	.31**	.23**
Amount of employees	**61**	.05	.083	.10	.06	.13*	.20**	.18**	.13*	.12*	.10	.19**	.15**	.16**	.17**	.21**	.15**	.12*	.18**	.27**	.15**	.15**	.24**	.24**	.29**	.25**	.18**	.15**	.16**	.13*	.23**	.26**	.21**
Requirements for company's control	**62**	.09	.08	.14*	.16**	.16**	.13*	.04	.06	.03	.10	.15*	.14*	.13*	.15**	.15**	.08	.14*	.16**	.27**	.17**	.21**	.26**	.32**	.22**	.25**	.17**	.09	.16**	.23**	.31**	.29**	.23**
Company's control level of detail	**63**	.12*	.12*	.15*	.18**	.12*	.14*	.07	.11	.10	.13*	.14*	.14*	.10	.16**	.13*	.08	.13*	.15*	.25**	.13*	.17**	.25**	.32**	.20**	.24**	.13*	.09	.16**	.22**	.31**	.32**	.22**
Company's communication system	**64**	.09	.01	.02	.16**	.11	.15**	.13*	.05	.06	.13*	.07	.08	.13*	.17**	.12*	.14*	.17**	.17**	.25**	.15**	.22**	.30**	.24**	.13*	.17**	.14*	.11	.14*	.15*	.29**	.24**	.21**

Note: ** = significant at the 0.01 level
* = significant at the 0.05 level
N = 295 companies

Explanation for intercorrelations:
very strong correlations
strong correlations
medium correlations

Table 49: Intercorrelations between complexity drivers (Part C)

Complexity drivers	ID	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Product structure/design	33	1															
Variety of parts and modules	34	.67**	1														
Variety of the applied materials	35	.57**	.66**	1													
Variance in product design	36	.38**	.35**	.33**	1												
Availability of materials or components	37	.38**	.34**	.47**	.34**	1											
Properties of modules and materials	38	.32**	.28**	.45**	.32**	.65**	1										
Product's degree of innovation	39	.37**	.36**	.41**	.34**	.33**	.34**	1									
Product life cycle length	40	.44**	.41**	.41**	.34**	.33**	.28**	.37**	1								
Technology change/innovation	41	.35**	.25**	.31**	.23**	.31**	.27**	.43**	.45**	1							
Number of different applied technologies	42	.47**	.46**	.42**	.37**	.40**	.37**	.42**	.44**	.60**	1						
Technology's complicacy	43	.42**	.44**	.38**	.39**	.33**	.31**	.42**	.39**	.52**	.77**	1					
Technology's combination	44	.40**	.40**	.36**	.33**	.34**	.30**	.38**	.35**	.40**	.61**	.62**	1				
Technology life cycle length	45	.38**	.35**	.34**	.23**	.27**	.28**	.24**	.41**	.40**	.53**	.47**	.63**	1			
Product software	46	.32**	.38**	.19**	.24**	.22**	.15*	.22**	.34**	.29**	.38**	.39**	.41**	.49**	1		
Data processing system	47	.28**	.26**	.22**	.18**	.28**	.23**	.15**	.33**	.31**	.38**	.35**	.33**	.38**	.66**	1	
Vertical range of manufacture	48	.27**	.26**	.30**	.24**	.33**	.30**	.25**	.28**	.32**	.35**	.33**	.37**	.27**	.07	.12*	1
Production system	49	.36**	.32**	.34**	.24**	.27**	.32**	.24**	.27**	.37**	.45**	.43**	.37**	.29**	.16**	.20**	.78**
Variety of processes	50	.32**	.38**	.39**	.24**	.31**	.31**	.30**	.32**	.30**	.37**	.35**	.37**	.36**	.18**	.25**	.57**
Amount of process interfaces	51	.38**	.39**	.35**	.25**	.27**	.27**	.31**	.30**	.30**	.42**	.44**	.47**	.43**	.29**	.34**	.45**
Process degree of cross-linking	52	.33**	.34**	.32**	.24**	.24**	.26**	.32**	.30**	.32**	.41**	.41**	.46**	.39**	.30**	.36**	.38**
Process standardization	53	.28**	.31**	.25**	.14*	.24**	.27**	.20**	.21**	.24**	.37**	.33**	.42**	.34**	.26**	.26**	.31**
Information flow's variety	54	.26**	.28**	.21**	.24**	.17**	.15*	.27**	.18**	.27**	.46**	.42**	.46**	.37**	.41**	.38**	.29**
Information flow's dynamics	55	.27**	.29**	.25**	.29**	.27**	.20**	.32**	.22**	.27**	.41**	.40**	.48**	.38**	.39**	.39**	.30**
Amount of hierarchical levels	56	.35**	.31**	.35**	.27**	.30**	.26**	.23**	.32**	.29**	.36**	.33**	.35**	.31**	.28**	.35**	.29**
Organization's/Company's size	57	.32**	.30**	.34**	.30**	.27**	.22**	.31**	.30**	.31**	.37**	.36**	.35**	.31**	.27**	.33**	.27**
Degree of centralization	58	.26**	.28**	.30**	.15**	.26**	.27**	.20**	.22**	.25**	.30**	.25**	.33**	.30**	.27**	.27**	.31**
Amount of simultaneous projects	59	.24**	.26**	.24**	.21**	.15**	.14*	.34**	.23**	.32**	.31**	.36**	.27**	.18**	.21**	.21**	.22**
Amount of simultaneous processes	60	.25**	.30**	.26**	.25**	.28**	.26**	.33**	.29**	.36**	.45**	.42**	.33**	.24**	.22**	.25**	.25**
Amount of employees	61	.25**	.21**	.24**	.24**	.16**	.15*	.26**	.20**	.31**	.30**	.33**	.28**	.16**	.17**	.17**	.26**
Requirements for company's control	62	.27**	.29**	.25**	.26**	.17**	.14*	.20**	.22**	.26**	.33**	.32**	.38**	.31**	.25**	.24**	.30**
Company's control level of detail	63	.27**	.29**	.27**	.30**	.17**	.13*	.24**	.23**	.25**	.31**	.30**	.39**	.27**	.21**	.21**	.29**
Company's communication system	64	.29**	.31**	.28**	.29**	.20**	.16**	.28**	.26**	.30**	.35**	.32**	.35**	.35**	.28**	.31**	.36**

Complexity drivers	ID	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
Product structure/design	33																
Variety of parts and modules	34																
Variety of the applied materials	35																
Variance in product design	36																
Availability of materials or components	37																
Properties of modules and materials	38																
Product's degree of innovation	39																
Product life cycle length	40																
Technology change/innovation	41																
Number of different applied technologies	42																
Technology's complicacy	43																
Technology's combination	44																
Technology life cycle length	45																
Product software	46																
Data processing system	47																
Vertical range of manufacture	48																
Production system	49	1															
Variety of processes	50	.58**	1														
Amount of process interfaces	51	.50**	.78**	1													
Process degree of cross-linking	52	.43**	.68**	.82**	1												
Process standardization	53	.35**	.52**	.58**	.67**	1											
Information flow's variety	54	.31**	.46**	.60**	.65**	.64**	1										
Information flow's dynamics	55	.30**	.46**	.58**	.61**	.56**	.86**	1									
Amount of hierarchical levels	56	.32**	.40**	.47**	.41**	.34**	.45**	.45**	1								
Organization's/Company's size	57	.32**	.41**	.51**	.49**	.35**	.47**	.48**	.80**	1							
Degree of centralization	58	.30**	.34**	.34**	.37**	.36**	.37**	.36**	.49**	.57**	1						
Amount of simultaneous projects	59	.27**	.33**	.37**	.33**	.32**	.42**	.49**	.38**	.46**	.32**	1					
Amount of simultaneous processes	60	.30**	.48**	.49**	.46**	.39**	.47**	.52**	.42**	.48**	.37**	.76**	1				
Amount of employees	61	.27**	.35**	.38**	.36**	.27**	.37**	.34**	.42**	.48**	.37**	.42**	.46**	1			
Requirements for company's control	62	.28**	.38**	.42**	.43**	.37**	.51**	.52**	.48**	.49**	.50**	.43**	.47**	.54**	1		
Company's control level of detail	63	.27**	.35**	.44**	.44**	.38**	.52**	.56**	.50**	.51**	.50**	.42**	.40**	.46**	.87**	1	
Company's communication system	64	.33**	.41**	.43**	.43**	.30**	.43**	.48**	.41**	.39**	.45**	.37**	.41**	.42**	.59**	.60**	1

Note: ** = significant at the 0.01 level
* = significant at the 0.05 level
N = 295 companies

Explanation for intercorrelations: ■ very strong correlations; ■ strong correlations; ■ medium correlations

Table 50: Total variance explained (Part A)

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	16.177	25.276	25.276	16.177	25.276	25.276	8.154	12.741	12.741
2	3.853	6.021	31.297	3.853	6.021	31.297	6.600	10.312	23.053
3	3.078	4.809	36.106	3.078	4.809	36.106	4.034	6.303	29.356
4	2.800	4.375	40.481	2.800	4.375	40.481	3.947	6.168	35.524
5	2.379	3.718	44.199	2.379	3.718	44.199	3.692	5.769	41.293
6	2.200	3.438	47.637	2.200	3.438	47.637	3.314	5.178	46.471
7	2.174	3.397	51.034	2.174	3.397	**51.034**	2.920	4.563	**51.034**
8	1.912	2.988	54.021						
9	1.513	2.364	56.386						
10	1.439	2.248	58.633						
11	1.421	2.220	60.854						
12	1.295	2.023	62.877						
13	1.196	1.869	64.746						
14	1.071	1.674	66.419						
15	1.025	1.602	68.021						
16	.980	1.532	69.553						
17	.970	1.516	71.069						
18	.937	1.464	72.533						
19	.877	1.371	73.904						
20	.831	1.299	75.203						
21	.809	1.264	76.467						
22	.765	1.196	77.662						
23	.732	1.143	78.806						
24	.728	1.137	79.943						
25	.660	1.032	80.975						
26	.638	.997	81.972						
27	.611	.955	82.927						
28	.588	.919	83.846						
29	.568	.888	84.734						
30	.546	.852	85.586						
31	.527	.824	86.410						
32	.504	.787	87.197						
33	.455	.712	87.909						

Table 50: Total variance explained (Part B)

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
34	.452	.706	88.615						
35	.428	.669	89.284						
36	.412	.644	89.927						
37	.407	.636	90.563						
38	.386	.602	91.166						
39	.371	.579	91.745						
40	.357	.557	92.302						
41	.349	.546	92.848						
42	.340	.532	93.380						
43	.316	.494	93.874						
44	.299	.467	94.341						
45	.294	.460	94.801						
46	.274	.427	95.229						
47	.267	.417	95.646						
48	.255	.398	96.044						
49	.251	.392	96.437						
50	.231	.361	96.797						
51	.211	.330	97.127						
52	.204	.319	97.446						
53	.193	.302	97.748						
54	.186	.291	98.039						
55	.169	.264	98.303						
56	.162	.254	98.556						
57	.156	.244	98.801						
58	.144	.225	99.025						
59	.130	.203	99.228						
60	.116	.182	99.410						
61	.106	.166	99.576						
62	.098	.153	99.730						
63	.093	.146	99.876						
64	.080	.124	100.000						
Extraction Method: Principal Component Analysis									

Table 51: Factor analysis on independent variables (Part A)

Complexity drivers	ID	First factor	Second factor	Third factor	Forth factor	Fifth factor	Sixth factor	Seventh factor
Information flow's variety	54	**0.76**						
Information flow's dynamics	55	**0.73**						
Requirements for company's control	62	**0.73**						
Company's control level of detail	63	**0.72**						
Process degree of cross-linking	52	**0.71**						
Amount of process interfaces	51	**0.71**	0.35					
Company's communication system	64	**0.63**						
Process standardization	53	**0.63**						
Organization's/Company's size	57	**0.62**						
Variety of processes	50	**0.62**	0.38					
Amount of simultaneous processes	60	**0.60**						
Amount of hierarchical levels	56	**0.59**						
Amount of simultaneous projects	59	**0.56**						0.39
Degree of centralization	58	**0.56**						
Amount of employees	61	**0.54**						
Number of different applied technologies	42		**0.67**					
Product structure/design	33		**0.62**					
Product life cycle length	40		**0.61**					
Technology's complicacy	43		**0.61**					
Variety of parts and modules	34		**0.59**					
Variety of the applied materials	35		**0.58**					
Technology's combination	44	0.40	**0.56**					
Technology life cycle length	45		**0.55**					
Product life cycle length	32		**0.55**					
Availability of materials or components	37		**0.55**			0.37		
Technology change/innovation	41		**0.53**		0.36			
Properties of modules and materials	38		**0.53**			0.37		
Product's degree of innovation	39		**0.51**					
Production system	49	0.42	**0.48**					
Vertical range of manufacture	48	0.41	**0.43**					
Variance in product design	36		**0.42**					

Table 51: Factor analysis on independent variables (Part B)

Complexity drivers	ID	First factor	Second factor	Third factor	Forth factor	Fifth factor	Sixth factor	Seventh factor
Customer structure	26			**0.71**				
Product variety	28			**0.68**				
Customer's amount	25			**0.65**				
Product range/Portfolio	29			**0.64**				
Individuality of customer demands	9			**0.55**				
Variety of customer requirements	8			**0.54**				
Customer's participation	27			**0.54**				
Demand's dynamics	10			**0.44**				
Technological progress	15				**0.69**			
Technological innovations & availability	16				**0.65**			
Market's change	12				**0.58**			
Market's globalization	14				**0.56**			
Competitor's dynamics	13			0.36	**0.53**			
Number & strength of competitors	11				**0.47**			
Market's economic factors	7				**0.45**			
Product software	46		0.34		**0.36**			
Data processing system	47				**0.35**			
Amount of suppliers	18					**0.75**		
Supply strategy or concept	19					**0.73**		
Quality uncertainty of delivered goods	20					**0.71**		
Uncertainty of delivery date	21					**0.67**		
Variety of supplied goods	17					**0.66**		
Environmental awareness in population	2						**0.84**	
Ecological conditions/factors	3						**0.80**	
Value change & value awareness	1						**0.68**	
Political framework conditions	4						**0.48**	
Legal factors	5						**0.46**	
Market's infrastructure	6				0.36		**0.37**	
Business objective's change frequency	23							**0.69**
Business objective's time pattern	24							**0.51**
Amount of different targets	22							**0.50**
Product portfolio change frequency	30							**0.45**
New product launch's frequency	31		0.40					**0.45**

Table 52: Overview about existing single approaches, focused on product (Part A)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Simon (1962, pp. 467-481)	M						
Imori *et al.* (1990, p. 503)	G						
Child *et al.* (1991a, p. 74)	R		R				
Child *et al.* (1991b, p. 65)	R						
Schulte (1992, p. 90)							R
Fischer (1993, p. 30)			R				
Ehrlenspiel (1995, pp. 420-421)						R, I	R
Fleck (1995, p. 189)	M	M					
Kaiser (1995, p. 17)	R						
Prillmann (1996, p. 113)			R				
Sanchez (1996, p. 121)	R						
Sanchez and Mahoney (1996, p. 66)	R						
Homburg and Daum (1997, p. 335)			A				
Jeschke (1997, p. 22)			R, A				
Jina, Bhattacharya and Walton (1997, p. 8)	R			R			
Mahoney (1997, p. 395)			R				
Pels, Wortmann and Zwegers (1997, p. 274)	M						
Adam (1998, p. 59)			R	R	R		
Bliss (1998, pp. 155-156)		R	R	R			
Bohne (1998, p. 240)	A	A	A	A			A
Eversheim, Schenke and Warnke (1998, p. 32)	R	R	R	R			
Göpfert (1998, pp. 139-140)	R, M						
Komorek (1998, pp. 272-273)	A	A	R	A			
Marshall (1998, p. 65)	G						
Piller (1998, p. 195)	R						
Schuh, Schwenk and Speth (1998a, p. 82)	R						
Schuh, Schwenk and Speth (1998b, p. 134)	R						
Wangenheim (1998a, pp. 73-74)				R	R		
Wildemann (1998, p. 58)	R	R	R				
Benett (1999, pp. 65-66, 133)	R	R	R, A				
Fisher, Ramdas and Ulrich (1999, p. 298)				R	R		
Haberfellner *et al.* (1999, p. 23)	R						
Marshall and Leaney (1999, p. 847)		G					
Muffatto (1999, p. 145)					R		
Nagarur and Azeem (1999, p. 125)			R				
Piller and Waringer (1999, pp. 37, 64)	R				R		
Reiners and Sasse (1999, p. 230)	A	A	R	R			

Table 52: Overview about existing single approaches, focused on product (Part B)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Schaefer (1999, p. 312)	R						
Wildemann (1999b, pp. 31, 34-36)				R	R		
Baldwin and Clark (2000, pp. 59, 64)	R, A				R		
Bliss (2000, pp. 42-44)	R	R	R	R	R		
Herzwurm (2000, p. 32)	R		R				
Olbrich and Battenfeld (2000, p. 17)	R, M	R, M					
Ulrich and Eppinger (2000, p. 200)					R		
Westphal (2000, p. 31)		R	R	R			
Göpfert and Steinbrecher (2001, p. 353)	R						
Haf (2001, p. 124)	R		R				
Hofer (2001, p. 46)					R		
Maune (2001, pp. 22-31)	R		R	A	R	R, I	R
Neff *et al.* (2001, pp. 31-32)			R	R			
Piller (2001, p. 226)	A	A	A	A	A		
Schuh and Schwenk (2001, pp. 79-84)	R	M				O	R
Schwenk-Willi (2001, pp. 79-80, 143-146)	R				R	O	R
Siddique and Rosen (2001, p. 1)					R		
Westphal (2001, pp. 135, 154)	R			R			
Franke *et al.* (2002, pp. 55, 71-75)	R, M	R, M	R, M		M	M	M
Herrmann and Seilheimer (2002, p. 669)				R	R		
Hesse, Fetzer and Warnecke (2002, p. 487)					M		
Klinkner and Risse (2002, p. 25)	M			M			
Korreck (2002, p. 146)			R				
Langlois (2002, pp. 19-20)		R					
Halman, Hofer and Vuuren (2003, pp. 149, 155)					R		
Junge (2003, p. 90)					R		
Katzke, Fischer and Vogel-Heuser (2003, p. 69)	R						
Wildemann (2003, p. 58)		R		R			
Wüpping (2003, pp. 50-51)	R		R		R		
Adam (2004, p. 21)				R			
A.T. Kearney (2004, p. 11)			R				
Dehnen (2004, pp. 9, 62-69)	R	R		R	R		
Ethiraj and Levinthal (2004, pp. 159-161)	R, M						
Friedrich (2004, pp. 25-27)	R, M		R, M		R, M		
Gerberich (2004, p. 247)	M	M		M	M		
Gräßler (2004, p. 131)							R
Keuper (2004, pp. 177-179, 198-203)	R	R	R	R	R	I	R

Table 52: Overview about existing single approaches, focused on product (Part C)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management **Author(s)**	**Single approaches focused on product**						
	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Klepsch (2004, p. 15)	R, M						
Mühlenbruch (2004, p. 46)	R	R	R	R	R	R	R
Perona and Miragliotta (2004, p. 110)	M						
Rall and Dalhöfer (2004, p. 624)	R		R				
Simpson (2004, p. 4)					R		
Thorogood and Yetton (2004, p. 4)		R	R				
Thun and Stumpfe (2004, pp. 170-171)			R		R		R
Blecker *et al.* (2005, p. 56)	R		R				
Böckle (2005, p. 12)				R	R		
Böhmann and Krcmar (2005, pp. 456-458)	R		R	R			
Fettke and Loos (2005, p. 21)				M			
Gausemeier and Riepe (2005, pp. 55-56)	R						
Greitemeyer and Ulrich (2005, p. 7)				G			
Hellström and Wikström (2005, p. 394)		G					
Klauke, Schreiber and Weißner (2005, p. 246)					R		
Klinkner, Mayer and Thom (2005, p. 34)	R						
Kroker *et al.* (2005, pp. 77-78)	R		R				
Schuh (2005, pp. 125-139)	R	R			R	R, I	R
Schuh *et al.* (2005, p. 22)					R		
Springer (2005, pp. 10-14)			R	R	R		
Anderson *et al.* (2006, pp. 22-25)	R						
Blecker and Abdelkafi (2006a, pp. 76-77)	R						
Heckmann (2006, p. 46)				R			
Lindemann and Baumberger (2006, p. 8)	M	M	R	R	R		
Lindemann and Maurer (2006, p. 43)	R	R			R		
Scheer *et al.* (2006, p. 157)	R	R	R				
Zenner (2006, p. 2)	R				R		
Adrian (2007, p. 1)					R		
Aurich, Grzegorski and Lehmann (2007, p. 14)	M		M		M		
Baumberger (2007, p. 100)	M	R	R	R	R		
Durst (2007, p. 31)	R		R				
Grotkamp and Franke (2007, p. 35)			A				
Grübner (2007, p. 332)	R						
Krause, Franke and Gausemeier (2007, p. 23)	R, M	R, M			R, M		
Lübke (2007, pp. 252-254, 264-266)				R	M	R	R, I
Marti (2007, pp. 70, 77)	R, M, A				R		
Mayer (2007, pp. 40, 119)	M			M	M		

Table 52: Overview about existing single approaches, focused on product (Part D)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Meyer (2007, pp. 63-65)	R, M, A		R				
Picot and Baumann (2007, pp. 222, 239)	R						
Renner (2007, pp. 15, 41)	M	M	R		M	M	M
Ruppert (2007, p. 68)	R, M						
Schuh *et al.* (2007a, pp. 53-54)	R		R				
Schuh *et al.* (2007b, pp. 3-4, 12)	M	M					
Steffen and Gausemeier (2007, p. 9)	R						
Straube and Mayer (2007, pp. 53-54)	R, M			M	M		
Wiermeier and Haberfellner (2007, p. 49)	R						
Wildemann (2007b, p. 21)	R		R				
Abdelkafi (2008, pp. 148-149)	R				R		
Aurich and Grzegorski (2008, pp. 316-317)	R, M, A		R, M, A				
Beetz, Grimm and Eickmeyer (2008, p. 39)	R						
Bick and Drexl-Wittbecker (2008, pp. 61, 103)	R	R	R				
El Haouzi, Thomas and Pétin (2008, pp. 47-48)	R	R					
Gabath (2008, pp. 34-38)	R	R	R		R		
Jagersma (2008, p. 241)			R				
Luger *et al.* (2008, p. 603)				R			
Peters and Hofstetter (2008, p. 16)	A			R	R		
Ponn and Lindemann (2008, pp. 150, 231, 240, 395-402)	R		R	M			R
Rafele and Cagliano (2008, p. 4)			R				
Schaffer *et al.* (2008, p. 3)					R		
Shamsuzzoha, Helo and Kekäle (2008, p. 1595)	G	G					
Terada and Murata (2008, p. 445)	R						
Thomas (2008, p. 113)	R				R		
Bohn (2009, pp. 255-259)	R		R				
Dombrowski *et al.* (2009, p. 257)			R, M				
Gumpinger, Jonas and Krause (2009, p. 202)						R	I
Helfrich (2009, p. 110)	R			R	R		
Kersten *et al.* (2009, p. 1136)	R		R				
Koppik and Meier (2009, p. 1174)				R			
Lasch and Gießmann (2009a, p. 210)	R						
Lasch and Gießmann (2009b, pp. 106-108)	R	R	R	R	R	R	R
Lindemann, Maurer and Braun (2009, p. 35)	R		G				
Newman (2009, p. 3)	R		R				
Redlich, Wulfsberg and Bruhns (2009, p. 556)	R						
Schoeller (2009, pp. 60-63)	R				R		

Table 52: Overview about existing single approaches, focused on product (Part E)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Bayer (2010, pp. 80-85)	R	R		R	R		R, M, A
Caniato, Crippa and Größler (2010, p. 63)	R						
Duerre and Steger (2010, p. 88)	G				G		
Flieder (2010, p. 497)	R						
Gießmann (2010, pp. 57-61)	R, M, A	R	R	R	R	R	R
Gomes and Dahab (2010, p. 59)		G					
Klug (2010, pp. 59-72)	R		R		R		
Pero *et al.* (2010, p. 120)	R						
Schuh, Arnoscht and Rudolf (2010, p. 1)					R		
Stirzel (2010, pp. 131-132)	R, M						
Stuhler, Ricken and Diener (2010, p. 60)			M				
Agrawalla (2011, p. 157)		G					
Brosch and Krause (2011, p. 1)		R			R		
Cao, Zhang and Liu (2011, p. 786)	R						
Gießmann and Lasch (2011, pp. 11-14)	R, M, A	R	R	R	R	R, I	R
Grösser (2011, p. 19)			R				
Haumann (2011, pp. 12-13)	A	A				A	A
Jacobs and Swink (2011, p. 681)					R		
Kersten (2011, p. 17)	R, A				R, A		
Manuj and Sahin (2011, p. 543)			G		G		
Möller, Hülle and Kahle (2011, p. 741)	G		G	G			
Reiss (2011, p. 78)			R				
Shamsuzzoha (2011, pp. 27, 35)	R						R
Shamsuzzoha and Helo (2011, pp. 318-319)	R	R			R		
Slamanig (2011, pp. 270-271)	R				R		
Wüpping (2011, p. 70)	R						
Beckmann (2012, p. 13)	G		G		G		
Buchholz (2012, pp. 213-214)	R	R	A	A	R, A		
Eilmann and Nyhuis (2012, p. 660)	R						
Eitelwein, Malz and Weber (2012, p. 79)	R						
ElMaraghy *et al.* (2012, p. 801)	R				R		
Flieder (2012, p. 32)	R						
Freund and Braune (2012, p. 57)					R		
Heydari and Dalili (2012, p. 63)		G					
Kersten *et al.* (2012, p. 156)	R						
Kesper (2012, p. 62)	R	R			R		
Lammers (2012, pp. 55-56)	R		R				

Table 52: Overview about existing single approaches, focused on product (Part F)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Meffert, Burmann and Kirchgeorg (2012, p. 449)		R					
Rüßler (2012, p. 12)				R			
Schapiro and Henry (2012, p. 3)		R					
Schawel and Billing (2012, p. 142)			R				
Wildemann (2012, pp. 143-149, 155-156)	R, M, A	R, M, A		M, A	R, M, A		
Wilke (2012, p. 70)	R		R		R		
Winkler and Allmayer (2012, p. 16)	M			M	M		
Boyksen and Kotlik (2013, p. 52)			R				
Seibertz, Brandstätter and Schreiber (2013, p. 165)		M					
Göpfert and Schulz (2013, p. 201)					A		
Götzfried (2013, pp. 43-45)	R				R		
Jäger *et al.* (2013, p. 343)	A		A				
Klein (2013, p. 80)					M		
Mayer and Volk (2013, p. 17)		M	M				
Meier and Bojarski (2013, p. 547)				R			
Ploom, Glaser and Scheit (2013, p. 15)					R		
Proff and Proff (2013, p. 146)				R			
Viehweger and Malikov (2013, p. 187)							I
Wildemann (2013, pp. 143-147, 155-156)	R, M, A	R, M, A		M, A	R, M, A		
Wüpping (2013, p. 142)	R		R				
Bauernhansl, Schatz and Jäger (2014, p. 347)	R, M		R, M				
Bittermann (2014, p. 58)					R		
Ehrlenspiel *et al.* (2014, pp. 359-361)	R				R		
ElMaraghy and ElMaraghy (2014, p. 4)	R		R				
Gebhardt, Bahns and Krause (2014, p. 75)	R						
Gemünden and Schoper (2014, p. 9)	R		R				
Grimm, Schuller and Wilhelmer (2014, p. 94)	R		R				
Jäger *et al.* (2014, p. 649)	A		A				
Jensen, Bekdik and Thuesen (2014, pp. 541-554)							G, I
Joergensen, Schou and Madsen (2014, p. 58)	R				R		
Kampker *et al.* (2014, p. 2)	R						
Keuper (2014, pp. 56, 61)			R			R	R
Kieviet (2014, pp. 60, 64)	R				R		
Kluth *et al.* (2014a, p. 226)	A						
Kluth *et al.* (2014b, p. 72)	A		A				
Koch and Renner (2014, p. 953)		R					
Koppenhagen (2014, pp. 115, 119)	R						

Table 52: Overview about existing single approaches, focused on product (Part G)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on product**						
Author(s)	Modular concept	Modular system	Standardization	Using same parts	Platform concept	Differential construction	Integral construction
Krumm, Schopf and Rennekamp (2014, p. 193)		M			M		M
Lanza *et al.* (2014, p. 65)		M	M				
Mattila (2014, p. 145)	G				G		
Mayer (2014, p. 27)	R						
Prodoehl (2014, p. 45)	R						
Schatz, Schöllhammer and Jäger (2014, pp. 688-692)	A		R, A				
Schoeneberg (2014a, pp. 18-21)	M, R		R				
Schoeneberg (2014b, p. 6)			R				
Schulz (2014a, p. 51)	M						
Tamaskar, Neema and DeLaurentis (2014, p. 125)	R	R					
Thiebes and Plankert (2014, pp. 180-183)	M			M			M
Zerres (2014, pp. 300-305)	R		R	R, A	R	R, I	R
Gepp *et al.* (2015, p. 1)	G		G				
Herrmann *et al.* (2015, p. 251)	M	M					
Königsreuther (2015, p. 33)		R			R		
Krieg (2015, p. 91)			R				
Kruse, Ripperda and Krause (2015, pp. 1-2)	M				M		
Martensson, Zenkert and Akermo (2015, p. 577)						R	
Schott, Horstmann and Bodendorf (2015, p. 36)	G		G		G	G	G
Schuh *et al.* (2015, p. 695)	R			R			
Theuer (2015, p. 3)	R	R					
Vollmar and Gepp (2015, p. 14)				G			
Total amount of literature sources, which are concerned with the specific complexity management single approach:	**158**	**60**	**90**	**56**	**87**	**19**	**29**

Table 53: Overview about existing single approaches, focused on product portfolio, process and organization (Part A)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on ...**							
	Product portfolio			**Process**			**Organization**	
Author(s)	Packaging	Reducing product range	Reducing of customers	Postponement concept	Standardization of processes	Modularity of processes	Delayering	Empowerment
Child *et al.* (1991a, pp. 75, 78)		R			R			M
Fischer (1993, p. 30)			R	M				
Hirzel (1993, p. 182)			R					
Reiß (1993a, pp. 8, 13-14, 21-22)							R	
Coenenberg and Prillmann (1995, p. 1245)				R, A				
Crichton and Edgar (1995, p. 13)	R							
Fleck (1995, p. 189)		R						
Kippels (1996, p. 3)							M	
Dombkins (1997, p. 428)								G
Homburg and Daum (1997, pp. 335-336)		R		M				
Jeschke (1997, p. 27)					R, A			
Bliss (1998, p. 157)	R							
Eversheim, Schenke and Warnke (1998, p. 32)				R				
Meijer (1998, p. 279)								R
Wildemann (1998, p. 58)	R							
Puhl (1999, p. 37)								R
Rapp (1999, p. 61)	R							
Baldwin and Clark (2000, pp. 59, 64)						R		
Battezzati and Magnani (2000, p. 414)				R				
Bliss (2000, pp. 39-41, 46-49, 197-204)	R	R	R	R				R
Olbrich and Battenfeld (2000, p. 45)								R
Westphal (2000, p. 31)				R				
Wildemann (2000, p. 7)		R	R					
Hoek (2001, p. 163)				R				
Maune (2001, pp. 25, 31-39)		R		R			M	
Piller (2001, p. 226)				R		R, A		
Schuh and Schwenk (2001, p. 83)	R							
Wildemann (2001, p. 5)				R				
Franke *et al.* (2002, pp. 21, 71)	M			M				
Zhou (2002, pp. 448-450)				R	R	R		
Aurich, Barbian and Wagenknecht (2003, p. 215)						R		

Table 53: Overview about existing single approaches, focused on product portfolio, process and organization (Part B)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on ...**							
	Product portfolio			**Process**			**Organization**	
Author(s)	Packaging	Reducing product range	Reducing of customers	Postponement concept	Standardization of processes	Modularity of processes	Delayering	Empowerment
Aurich and Wagenknecht (2003, p. 662)						A		
Armbruster and Kieser (2003, p. 163)								M
Dehnen (2004, p. 155)					R			
Gerberich (2004, p. 247)				M				
Hanenkamp (2004, p. 69)		R						
Keuper (2004, pp. 184, 193)	R							R
Mühlenbruch (2004, pp. 46-48)	R			R				
Böhmann and Krcmar (2005, pp. 456, 459)	R	R	R	R				
Geimer (2005, p. 42)		R						
Hoole (2005, p. 4)				R				
Müller (2005, p. 720)	M							
Schuh (2005, p. 129)	R							
Stephan (2015, p. 36)	R							
Wallenburg and Weber (2005, p. 48)				G				
Blecker and Abdelkafi (2006a, p. 77)						R		
Blecker and Abdelkafi (2006b, p. 923)						R		
Blecker and Abdelkafi (2006c, p. 162)				G				
Meyer, Walber and Schmidt (2006, pp. 532, 535)						R, M		
Spath and Demuß (2006, p. 482)					R			
Aurich, Grzegorski and Lehmann (2007, p. 15)					M			
Durst (2007, p. 31)			R	R				
Grotkamp and Franke (2007, p. 35)		R, A						
Hyötyläinen and Möller (2007, p. 305)	R							
Lübke (2007, pp. 254-255, 262)	R			R				
Meyer (2007, p. 64)			R	M, A	R	M, A		
Straube, Doch and Huynh (2007, p. 37)					R			
Abdelkafi (2008, p. 154)						R		
Huang and Li (2008, p. 111)				R				
Laqua (2008, p. 27)		R						
Mogilner, Rudnick and Iyengar (2008, p. 212)		R						
Rafele and Cagliano (2008, p. 4)					R			

Table 53: Overview about existing single approaches, focused on product portfolio, process and organization (Part C)

Explanation according to complexity strategy:
R Reduction of complexity
M Mastering of complexity
A Avoidance of complexity
I Increasing of complexity
O Outsourcing of complexity
G General for complexity management

	Single approaches focused on ...							
	Product portfolio			Process			Organization	
Author(s)	Packaging	Reducing product range	Reducing of customers	Postponement concept	Standardization of processes	Modularity of processes	Delayering	Empowerment
Thomas (2008, p. 113)						R		
Beimborn *et al.* (2009, p. 3)					R			
Bohn (2009, p. 261)				M				
Lasch and Gießmann (2009a, p. 210)	R							
Lasch and Gießmann (2009b, pp. 108-110)	R	R	R	R	R			
Schulze, Mansky and Klimek (2009, p. 1)				M				
AlGeddawy and ElMaraghy (2010, p. 5281)				R				
Bayer (2010, pp. 75-79)	R	R		R, M				
Blockus (2010, p. 287)		G	G					G
Gießmann (2010, pp. 62-70)	R	R	R	R	R, A	R, A	R	R
Keil (2010, p. 6)								R
Klug (2010, p. 55)				R				
Yang and Ji (2010, p. 183)							R	
Yang and Yang (2010, p. 1909)				R				
Brosch and Krause (2011, p. 1)				R				
Gießmann and Lasch (2011, pp. 15-20)	R	R	R	R	R, A	R, A	R	R
Kersten (2011, p. 17)		R			R			
Reiss (2011, p. 80)					G			
Beckmann (2012, p. 13)		G		G				
ElMaraghy *et al.* (2012, p. 801)						R		
Lammers (2012, p. 55)	R							
Winkler and Allmayer (2012, p. 16)				M				
Biedermann and Lindemann (2013, p. 495)	G							
Göpfert and Schulz (2013, p. 202)				M				
Jäger *et al.* (2013, p. 343)					A			
Nagengast, Heidemann and Rudolph (2013, p. 668)		R						
ElMaraghy and ElMaraghy (2014, p. 4)				R				
Jäger *et al.* (2014, p. 649)		R			A			
Keuper (2014, p. 61)								R
Kluth *et al.* (2014a, pp. 226-227)		R			A			
Kluth *et al.* (2014b, p. 72)		R			A			

Table 53: Overview about existing single approaches, focused on product portfolio, process and organization (Part D)

Explanation according to complexity strategy: R Reduction of complexity M Mastering of complexity A Avoidance of complexity I Increasing of complexity O Outsourcing of complexity G General for complexity management	**Single approaches focused on ...**							
	Product portfolio			**Process**			**Organization**	
Author(s)	Packaging	Reducing product range	Reducing of customers	Postponement concept	Standardization of processes	Modularity of processes	Delayering	Empowerment
Mattsson *et al.* (2014, p. 212)								G
Schatz, Schöllhammer and Jäger (2014, pp. 691-692)		R					M	
Schulz (2014b, pp. 218-220, 225)				M				
Wölfling (2014, p. 17)				G	G	G	G	
Zerres (2014, pp. 300, 306)				R				
Braun (2016, p. 308)							R	
Schott, Horstmann and Bodendorf (2015, p. 36)	G	G						
Total amount of literature sources, which are concerned with the specific complexity management single approach:	**23**	**25**	**11**	**40**	**20**	**15**	**9**	**14**

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Complexity drivers in manufacturing companies: A literature review

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Bei der Auswahl und Auswertung des Materials sowie bei der Herstellung des Manuskripts habe ich Unterstützungsleistungen von folgenden Personen erhalten: *Prof. Dr. rer. pol. Rainer Lasch*

Weitere Personen waren an der geistigen Herstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich nicht die Hilfe eines kommerziellen Promotionsberaters bzw. einer kommerziellen Promotionsberaterin in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

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Stuttgart, den 31. Oktober 2018

gez. Wolfgang Vogel