Chapter 3
Managing Complexity Within the Engineering of Product and Production Systems

Rostami Mehr and Arndt Lüder

Abstract Changing conditions on costumer, material, and technology market force producing companies to decrease duration of product and production system development. Especially in case of complex products like cars, this reduction leads to a strategic need for parallel development of products and production systems. Thus automotive industry organizes a complex interplay between product engineering and production system engineering within the *new product and production system development processes* (NPPDP).

This chapter discusses complexity challenges from automobile manufacturing that NPPDP have to cope with, and surveys strengths and limitations of complexity management methods for production system development. As no complexity management method can fully address the NPPDP challenges, the chapter derives types of NPPDP requirements and discusses a future framework for managing the complexity in NPPDP.

Keywords Complexity management · Interlinked product and production system engineering · Requirements for engineering processes

3.1 Introduction

Due to trends such as globalization and increased digitalization, manufacturing companies today operate in an environment very different from that a few decades ago. On the one hand, globalization has provided unique opportunities to companies to attract customers, to split up the work among specialized contributors, and to purchase services and materials from all over the world. On the other hand, it has increased competition as a result of the increasing number of international players. Hence, today customers have more choices and act in a buyers' market.

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To respond to such global opportunities, companies must adapt their product and/or service portfolio to be able to satisfy various customer requirements, leading to the consideration of different market niches. The resulting market segmentation, with sharply delineated products tailored to local needs, increases the required amount of product/service variations and adaptations. This problem is intensified in companies and domains that basically have a high number of product variants like the automotive industry or home appliances.

In addition to the increasing number of products and product variants, the duration of product lifecycles is decreasing rapidly (MirRashed et al. 2016). Apart from this, the speed of technological changes has dramatically increased in the last few decades. Such rapid changes have increased the time pressure on companies to develop and introduce new products.

Furthermore, the development of new products takes place in an increasingly international environment. Several companies and several departments collaborate in a big network, an engineering organization (VDI 2010), to develop a product or to adjust existing products to new markets or to new customer requirements (Lindemann et al. 2006). The number of connected and parallelized processes in development procedures is rising (MirRashed et al. 2016). Products are getting more complex. The interlinking of products on production processes, their mutual impact, and the required resources for them are growing (Lindemann et al. 2006).

In summary, market and environment conditions of manufacturing companies are becoming increasingly complex, and, consequently, these complexities affect the manufacturer as an organization. As a result, the complexity of *new product and production system development processes* (NPPDP) increases. In this chapter, the NPPDP is defined as the complete network of engineering activities (taking design decisions based on available engineering information and skills and knowledge of engineers and using appropriate tools) that are required to design a new product (or set of product variants) and the production system required to produce this (these) product(s). In the automotive industry, the NPPDP covers the design of a car (with car body, power train, and all internal technical and other elements) and the different production systems to create them. This chapter illustrates this complexity and draws conclusions on the engineering process embedded in the NPPDP.

The dilemma of complexity has attracted growing attention as the effects on different parts of organizations became increasingly evident. In recent decades, an increasing number of researchers have attempted to respond to the following *Complexity-related Research Questions* (CrRQ):

CrRQ1: How can an organization deal with the growing complexity within new product and production system development processes (NPPDP)?

To answer this question, three main research activities have been combined: literature research, collecting evidence from practice, and experiments. Together they all have enabled the identification of available complexity management approaches, their evaluation with respect to their applicability within the NPPDP in the automotive industry, and the identification of required improvements leading to the development of a new complexity management framework.

This complexity management requires appropriate methodological and technical support within the engineering organization. This support strongly affects the quality of the management and, finally, the quality of the engineered systems themselves leading to the following question.

CrRQ2: What are requirements to the engineering organizations intending to integrate stronger complexity management within new product and production system development processes (NPPDP)?

The answer to this question is based on the consideration of a new complexity management framework. In this chapter, a future complexity management framework is drafted by identifying its main building blocks and sketching required IT technologies needed within.

While answering the "Complexity Related Research Questions," this chapter will contribute to the research questions*RQ1a*: "What are typical characteristics of engineering processes for long-running software-intensive technical systems?" and *RQ1b*: "What are requirement areas from engineering processes for long-running software-intensive technical systems that require informatics contributions?" mentioned in Chap. 1.

Based on the background of the authors, the automotive industry will be applied as running example within this chapter. In this industry, complexity management has a significant impact on the efficiency and quality of engineering and helps reduce the cost and risk of NPPDPs.

To answer the CrRQ in relation to engineering within the automotive industry, this chapter is structured as follows.

Section 3.1 introduces as focus of research new product and production system development processes (NPPDP) that address the strategic need for parallel development of products and process variants.

Section 3.2 discusses complexity challenges from automobile manufacturing that NPPDP have to cope with.

Section 3.3 surveys complexity management methods for production system development.

Section 3.4 summarizes NPPDP types of requirements.

Section 3.5 discusses a framework for managing the complexity in NPPDP.

3.2 Complexity Challenges

The most important driver of complexity in industry is the product (Schoeller 2009). The product is formed on the basis of customer needs. Customer needs are affected by trends like regionalization, fragmentation, and saturation (Maune 2011).

Regionalization can be illustrated in the example of the automobile variants sold in different areas. The station wagons are the models that are in highest demand in Europe, but in Asia, sedans sell much better than station wagons. Fragmentation becomes visible in the increasing electrification of cars leading to similar cars with different drive chain concepts, going beyond different fuels, such as petrol

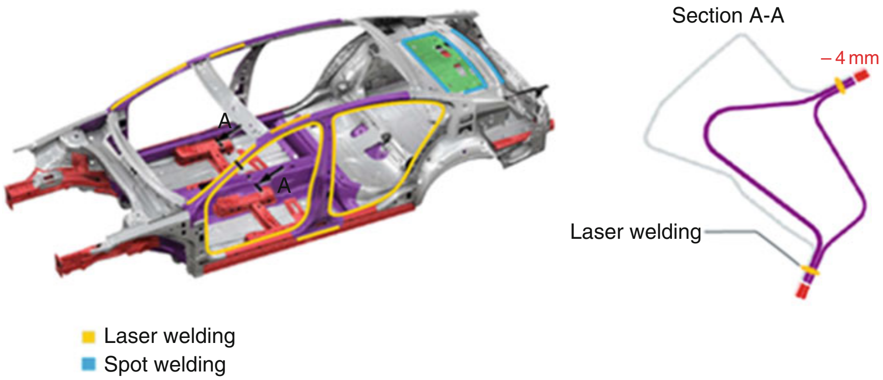

Fig. 3.1 Example of laser welding impacting product and production system engineering

and diesel, now also including completely electrical-driven cars, hybrid cars, and hydrogen or natural-gas-driven cars. The third trend that impacts customer demand—saturation—is a trend most prominent in west-European countries, North America, and Japan. Here the number of licensed cars is stagnating. It requires automobile manufacturers to differentiate and individualize their products forcing both other trends. Premium car manufacturers could benefit from this trend (Wemhoener 2005), but for high-volume manufacturers and manufacturers of commercial vehicles, the trend of saturation can be very challenging.

Another factor that has a significant impact on products is regulation. As automobiles significantly affect the environment and accordingly influence society, the legislators stipulate the requirements that must be followed by manufacturers. Such legislation could vary from country to country (Maune 2011). Most prominent legislation trend is related to reducing emissions. There are two fields considered. On the one hand, the emission of the product (the car) shall be reduced based on improved drive chains or reduced overall mass. On the other hand, the energy consumption of the production system needs to be reduced resulting in considerations related to production technologies, such as low-energy car body welding or even replacing welding by gluing. Figure 3.1 depicts an example affecting both the product and the production system. Here new joining methods in car body production, which contribute to reducing the weight of cars, are presented. As is obvious, legislation is one of the important drivers for developing and deploying new technology that affects products and production systems.

The third factor refers to the changes in technologies, such as the introduction of a new material or new production techniques. The applications of new materials like high-strength steel, hot-formed parts, aluminum, sandwich materials, fiber composites, and so on, attract increasing attraction. Although the applications of these materials have been common in the premium car segment for some time, recently these materials have become more common in high-volume cars. The increasing number of materials in the body of cars generates challenges in selecting

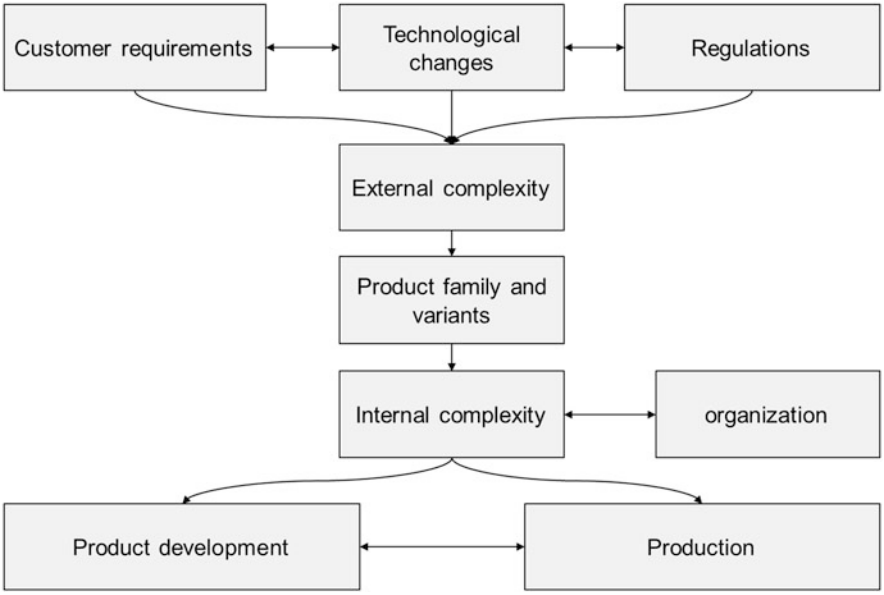

Fig. 3.2 Internal and external complexity in automobile manufacturing (Brosch 2014)

and adjusting the production process and, thereby, the selection of appropriate production resources within the production system engineering.

These three factors—customer requirements, rapid technological changes, and regulations—can be categorized as factors shaping *external complexity*. External complexity has a direct impact on product characterization. As a consequence, the product shapes the organization and exerts an enormous influence on *internal complexity* as depicted in Fig. 3.2. Transferring all three influencing factors to the product and shaping the product in a way that responds exactly to all requirements of these external factors, is challenging. The exact matching of product structure and external requirements could create an important competitive advantage for the organization through cost and risk reduction and efficiency increase.

3.2.1 General Problem in Practice

New product and production system development processes (NPPDP) are considered complex processes, especially in the automobile industry. The basis for this consideration is, on the one hand, the complexity of the product and, on the other hand, the complexity of the production system required for the product.

Cars are complex products due to the high number of components used in the depth and breadth of the product. Product structure breadth is defined by the number of components used for the parent item and the depth of the product is defined by the number of levels in the product hierarchy (Gabriel 2007). Similarly, the complexity of the production system depends on the number of required production process steps and their interlinking in a process network.

Product and production system complexity can have different influences on different parts of an organization engaged in development processes. The trends of individualization have led to an increased number of product variants, and a high number of variants intensify the time intensity in NPPDP. Time intensity in a complex project intensifies the complexity because of the increased number of activities that must be completed more or less at the same time. It also causes increases in the received information at the same time (DeVries 2005).

Increased amounts of information do not necessarily represent the same quality of information. Owing to time pressure, the quality of information could decrease. Again, insufficient quality of information causes extra complexity. This is akin to the project management triangle, as changes in the time of activity completion may impact quality and cost (PMI 2017).

Following the increased market competition, NPPDP are accelerated to decrease the time-to-market. On the one hand, the approach of simultaneous engineering enables organizations to reduce time-to-market, while on the other hand it requires starting activities in NPPDP in a partially or completely parallel manner. This, again, results in an increasing information flow between the departments engaged in development.

Since, in the early phase of NPPDP projects, car designs are mostly conceptual and not completed, the required information for production system engineering is not presented in detail. Nevertheless, production planning engineers start their task in an early phase parallel to the designers. Therefore, the number of changes during the development phase of the production system could rise, following the changes in car design. The increased number of changes under time pressure could again intensify time pressure and increase complexity levels more than before (Benedikt et al. 2012).

Another effect of the high number of variants is the so-called *recourse leveling*. In projects like the development of cars with a high number of variants and models, companies first develop the main variant of the car—that is, the model sold the most—and then they develop next variants and models, in sequence. This strategy enables them to first stabilize the production line for the first variant, and then adjust the production line for the next upcoming variants. This strategy also provides them the ability to manage fluctuations of the required work for the development of high variant cars. Unfortunately, this approach causes a production system planning without having the exact information of the upcoming variants. The phenomenon of incomplete information in production development processes generates more uncertainty and, accordingly, more complexity (MirRashed et al. 2016).

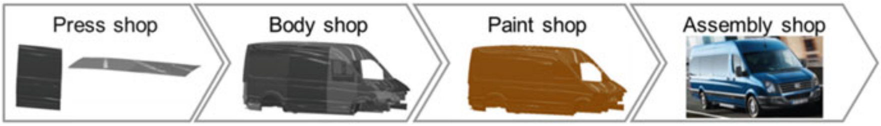

Fig. 3.3 Four main fields of car manufacturing

3.2.2 Products and Production Systems

As mentioned earlier, the overall complexity of the NPPDP comes from the complexity of the product, the complexity of the production system, and their dependencies. To make this complexity more visible in the following the car production process is reviewed.

Usually, the overall car production process is chronologically divided into four fields: press shop, body shop, paint shop, and assembly shop (see Fig. 3.3).

This division of labor supports the car production companies to manage their internal organization and processes within and between these fields.

The production starts with the press shop where the necessary metal sheets for a car are stamped out of steel coils. A typical body of car includes approximately 200 sheet metal parts for passenger cars and almost 250 sheet metal parts for light commercial vehicles.

In the subsequent body shop, these metal sheets are joined together. The most common joining methods include spot welding, stud welding, weld bonding (combination of adhesive and spot welding), clinching, MIG arc welding, and laser welding.

Next, the created car body is coated within the paint shop. Here, different layers of different materials are applied and dried in coating and oven lines. Finally, within the assembly shop, the car body is assembled with all necessary further car parts, including car wire harness, seats, power trains, lights, and windows. Up to 10,000 additional parts may have to be mounted to the car.

It shall not be neglected that the parts to be mounted and their production are also complex, especially for the power train.

The above-mentioned four fields of production constitute more detailed organizational divisions, for instance, the body shop is divided into four segments for platform, side walls, main body, and hang-on parts, while the assembly shop is subdivided into suspension system, engine, gearbox, seats, glasses, and plastic parts.

This division of the manufacturing process activities also forms the development processes and finally impacts the design of the organizational units for production development. Thus, the production development processes are segmented similar to the production processes.

3.2.3 New Product and Production System Development Process

The NPPDP in the automotive industry, designed for the joint development of car and production system, is established by six teams of engineers:

- The *project management team* has the job of coordinating and controlling the whole planning processes including the support of other planning team during the product development through the construction of prototypes, feasibility studies, and tests of the production technologies and processes.
- The *car engineering team* is responsible for the development of the product, that is, the car including the design and the evaluation of required manufacturing processes.
- The *production systemengineering teams of press shop, body shop, paint shop, and assembly line* are responsible for determining the required tools, machinery, technologies, and processes of manufacturing for the product developed. They also influence products in order to ensure the manufacturability, reduce the total project cost, and achieve the desired quality of the product.

The inner part of Fig. 3.4 depicts the work of these engineering teams.

Usually, the *car engineering team* starts the product engineering with design and construction of the product, which is accompanied by building first prototypes. Mostly at the same time *production system engineering teams* of the four different production system fields start to plan production facilities. When the *car engineering team* has reached the product release state, the *production system engineering teams* can finish the production system planning and start with supplier acquisition, detailed engineering, building and commissioning the production system. After product

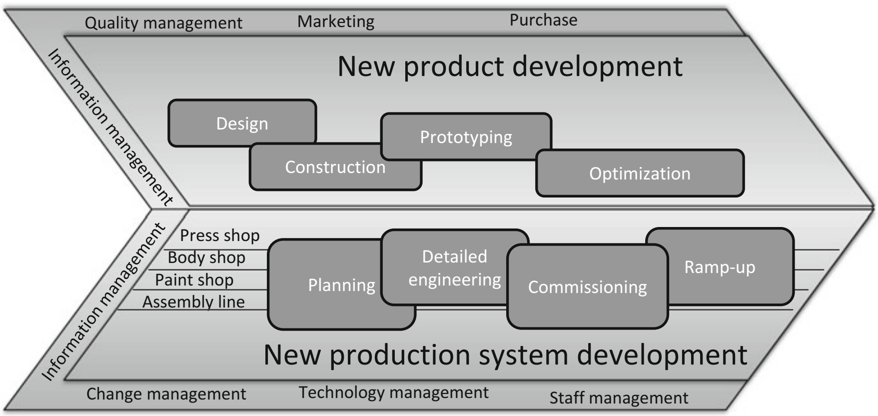

Fig. 3.4 General structure of NPPDP

release and in parallel to production system detailed engineering and commissioning, the prototyping and testing of product will take place by the *car engineering team*.

It becomes clear that the engineering activities of the different engineering teams run in parallel and constitute sequences of activities to conceptualize, construct, and commercialize a product. These activities are mostly mental and organizational instead of physical (Oyama et al. 2015), and, in addition, interlinked with each other. Two examples are the identification of problems or optimization possibilities within product engineering that change the product (like reinforcement of car body for optimization of crash test behavior) and lead to necessary changes in production system detailed engineering and, consequently, the identification of a problem regarding manufacturability by a supplier (like discovering the collision of manufacturing tools with the product) leading to a product change within the product construction. In addition, the named engineering processes are linked with additional functions of the overall company like quality management, purchase, and marketing on the product side and change management, technology management, and human resource management on the production system side.

It shall not be neglected that the described process is in some sort iterative. By quasi-parallel product and production system release prototyping and testing of product will take place. Thereafter, design engineer can start to discover problems or optimization possibility related to the product. The emerging product changes can have impact on the production system design. For example, the reinforcement of car body for optimization of crash test behavior can lead to additional handlings in car body welding. In addition, also on the production system side, improvement possibilities related to manufacturability or economic issues can be identified, possibly leading to requests for product change. An often relevant example is the identification of collisions of the welding tool with the car body requiring a shift of the welding spot location.

Beyond these overall company function, the information management has an important impact on the overall engineering organization, as it is responsible for the creation, exchange and storing of engineering information along the complete life cycles of product and production system. Information management covers all IT hardware and software such as Product Life Cycle Management (PLM) systems, databases, and servers.

The number of individual activities related to each named organizational unit might be very high. In automobile industries, this number can exceed a thousand activities (Kirchhof 2003). This results in enormous flow of information. One illustration for this fact could be the engineering of the body shop. The VDI Guideline 4499 (VDI 05/2011) introduces more detailed subphases for the planning phase mentioned in Fig. 3.4. This guideline defines the *concept planning phase* covering activities like finding production concepts, joining sequence planning, and geometrical validation, all intending to detail the production process to be executed. The next subphase is the *detailed planning* targeting the discussion of required production resources covering, for example, jigs and fixtures planning, material flow planning, and ergonomics analysis. This phase is closed by cost calculation and offline programming (see Fig. 3.5).

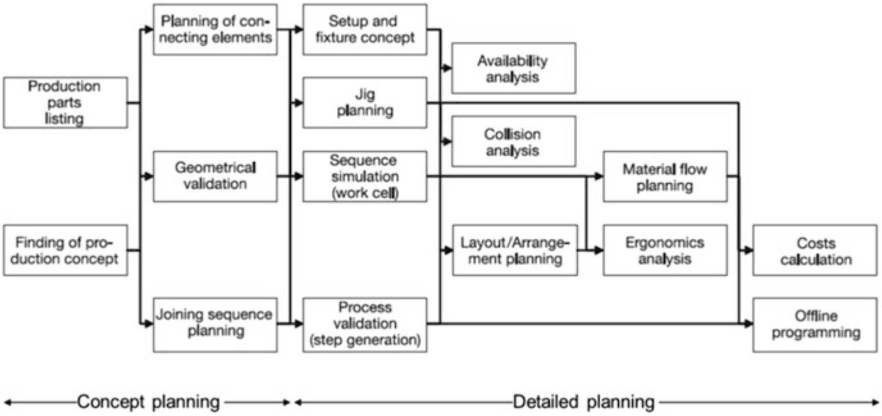

Fig. 3.5 Body shop production development (VDI 05/2011)

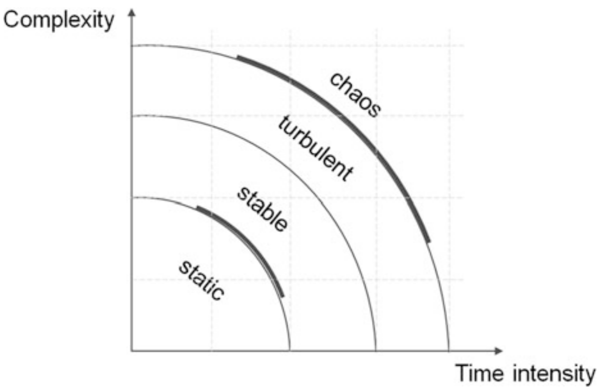

Fig. 3.6 Dynamic complexity of NPPDP

Originating from the changing market conditions, the complexity of the NPPDP has additionally increased by uncertainties regarding time to market, market demand, fluctuation of demand, available technology, speed of development of new technologies, and required resources such as human resources and capital (Grussenmeyer and Blecker 2013). With the presence of features, like a high number of involved engineering decisions (diversity) that are strongly interrelated by required information exchange (connectivity), and frequent changing bordering conditions (uncertainty), NPPDP can be categorized as a complex. In addition, their duration, dynamics, and human labor-intensiveness makes NPPDP time intensive. NPPDP are usually turbulent following the high dynamics and the strong dependencies between engineering activities and increasingly show a tendency to become chaotic (see Fig. 3.6). Thus, there is a strong need for management mechanisms to handle complexity before becoming chaotic.

3.3 Complexity Management for Production System Development

Several research studies have worked on complexity and approaches to deal with complexity. In the following, some studies shall be discussed opening up the existing broad scope and summarizing the main features applied in these approaches.

In complexity management sciences, there are approaches based on a holistic view of a system/organizationthat recommend steps to manage complexity. As these approaches are based on the strategy of a comprehensive view of systems, the applications of these approaches in praxis are very challenging. Two examples in this field are the work of Vogel (2017) and the work of Budde (2016).

Vogel (2017) introduced a *comprehensive complexity management* approach for resource planning, which has the following four steps: complexity analysis, complexity evaluation, application of complexity strategies, and complexity planning and control. The application of such approaches in praxis requires supporting tools to evaluate or identify a suitable strategy of complexity, which could vary drastically from case to case.

Budde (2016) introduced a parameter that provides better visualized understanding of complexity named *Complexity Value Level* (CVL). This parameter delivers a quantitative value that shows whether an organization is a complexity master or outperformer, market performer, and complexity underperformer. Based on this complexity index, an organization can define actions to improve its CVL and improve complexity management. Even though providing a quantitative index for complexity is very helpful, still this index could not help in defining strategies for specific complexity drivers to manage or reduce complexity.

On the other hand, there are several approaches addressing predefined complexity drivers and providing methodologies to handle them. For instance, the *variant management strategy* is a common approach to solve the problem of complexity caused by variants (Thiebes and Plankert 2014). Since these strategies are based on single complexity drivers, usually the overall complexity of the production system will remain unaffected. This is known as remaining complexity. The limitation of variant management in solving complexity in the early phase of production development processes is an example of this deficit for such approaches.

Finally, there are approaches addressing sets of complexity drives. Schuh (2005) and Schuh et al. (2011, 2015, 2016) introduced a framework to evaluate the complexity in NPPDP. This framework includes three main sections: evaluating complexity by using complexity drivers, analyzing the interdependencies between drivers, and segmenting or rating the drivers. This evaluation of complexity drivers serves as a basis to define proper methods to manage complexity by dealing with its causes and origin.

Meier et al. (2005) suggested a comprehensive approach for managing the complexity of products by means of, inter alia, variant management and managing the complexity of processes through lean management.

Daryani and Amini (2016) drew a five-step process for complex organization management by understanding the complexity type, investigating the causes of complexity, identifying solutions, selecting an effective solution, and implementing and evaluating the selected solution. They intended to provide decision-making assistance in complex situations.

Lasch and Gießmann (2009) introduced a complexity management method enhancing the well-known PCDA cycle. They aggregated existing engineering methodologies like variant management, ABC analysis, failure modes and effect analysis (FMEA), and impact matrices to one larger methodology.

For production organizations, Marti (2007) introduced a complexity management model with three steps: strategy and product lifecycle assessment, product complexity management, and driving guidelines for action. The first step includes analyzing the strategy of the company and product positioning in the market and its lifecycle. The second step analyzes product details for optimization of its architecture. And the last step provides guidelines for action in accordance with the findings in the first two steps.

In total, there is no approach available that addresses the intensified dynamic complexity caused by time pressure, incomplete information, and strong linking of engineering activities as given in the NPPDP.

To gain an essence of the available approaches in complexity management science, the next section investigates the common features of these complexity management approaches.

3.3.1 System Thinking

The system engineering sciences have strong interrelations with complexity management sciences. Within systems engineering, a system is defined as a collection of elements that are interrelated and distinct from the environment (Chen et al. 2009). A system is designed for a purpose, that is, predefined goals or objectives (Fuchs 2018). The term “element” is applied to any part of a system (e.g., organizational units, employees, documents) and, therefore, can also be used for subsystems (Checkland 1999). A system may have interconnections with its environment.

As mentioned earlier, the definition of complexity has strong interconnection with system definition. Complexity of systems is defined as a high number of interconnected elements that have a variable status. This variation can include but is not limited to the number of elements, their interaction within the system, and their interaction with the environment. To better understand the complexity of a system, it is strongly recommended to consider the system within its interacting elements and its environment, that is, to consider complexity from the systems thinking side.

Especially Maurer (2007) emphasizes a systematic approach toward complexity management to resolve the challenge of missing clarity. The identification of the system with elements and interactions as well as its environment helps to define the origins of complexity and their impact.

Thus, understanding the NPPDP as a system with its structure and behavior is the first main requirement within complexity analysis and management.

3.3.2 System Analysis

System analysis provides tangible fundaments to identify the origin of complexity.

The structure of interactions among system elements can be, for example, more modular oriented, forming clusters of elements that are stronger linked while interactions among clusters are only sparse. Another example is the integral structure where all elements interact with each other more or less equally strong. It is obvious that changes in the behavior of one element will have different impacts on the behavior of the other elements in both structures (Fuchs 2018). Therefore, the structures may provide information on complexity.

Analyzing the system reveals also the type of interactions between the elements. Elements can be disconnected from other elements, have one-way connection, or can be connected which each other in both directions. These interactions can be represented by dependency structure matrices (Jacob and Paul 2016) or by graph-based methods (Maurer 2007). Different interaction types will impact complexity in a different way.

Nevertheless, it is difficult, up to impossible, to identify all interactions among the elements of an NPPDP (Malik 2016). Therefore, a method has to be considered to collect relevant information or sort gathered information in an effective manner.

In addition to the static analysis of the system also the dynamic features of a system (especially in the case of an NPPDP) are relevant. During the system lifetime, the status of system elements as well as interactions of system elements may change. The speed of changes is one of the determining factors in complexity. In some works, this factor is called “fast flux,” expressing the transient nature of the organization and its environment (Schwandt 2009).

System analysis by itself does not result in complexity management, but represents the fundament of the system under consideration, enabling better interpretation, management, and (finally) improvements (Maurer 2007). System analysis also reveals potentials in two ways: optimization of the system structures such as eliminating redundant elements or dependencies, clustering of elements to build modules, and building a path to trace complexity effects on the system.

3.3.3 Drivers and Effects Analysis

As mentioned earlier, the system analysis shall be the foundation for an analysis of the complexity drivers and their impact on the system or subsystems. Successful analysis of complexity drivers and effects is a mandatory enabler for appropriate complexity management methods. Indeed, an initial concern regarding the system

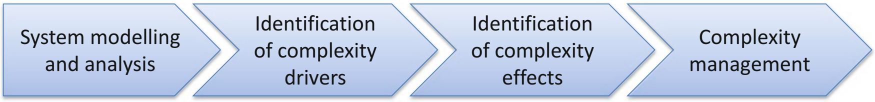

Fig. 3.7 General complexity management process for NPPDP

definition is the origin of complexity. Sources of complexity and their impact can be located in different system parts (Brosch 2014; Maurer 2007; Velte et al. 2017).

Several methods have been developed to find the origin of complexity. The first step of all methods is collecting information. Based on information gathered in the system analysis [from available documents and experts (Weber et al. 2014)] methods from Cause and Effect Analysis or Root Cause Analysis (RCA) can be applied (Lee et al. 2018).

Beyond the application-case-related, cause-and-effect analysis, there are also generalizations of complexity causes. For example Velte et al. (2017), surveyed complexity management and categorized complexity drivers. Thereby, three groups of complexity drivers related to production systems have been identified: *internal complexity* including product, organization, process, order fulfillment; *interface complexity* including purchase, communication, and sales; and *external complexity* covering customer, competition, and legislation.

Wildemann (2012) has also categorized the complexity drivers in three groups: company structure based drivers, information systems based drivers, and communication system based drivers.

Similar to complexity causes the complexity impacts are various. Most often, high-level impacts are related to project costs (Sinha 2014), production (Kieviet 2014), and quality (Lasch and Gießmann 2009).

3.3.4 Summary

Summarizing the considerations in this section, there are two main types of methods relevant within complexity management for NPPDP: holistic methods and special driver related methods. These methods all share the same basic structure depicted in Fig. 3.7. Usually, they start with modeling and analyzing the system of interest. Based on this analysis, complexity drivers and complexity effects are identified and used for the definition of complexity management measures.

However, both approaches mentioned have their specific drawbacks. The holistic approach lacks details for industrial usage. These methods are too general and face many unclear situations, making them hard to apply in industrial practice. The methods targeting special complexity drivers might not take care of relevant complexity drivers for the system of interest. Thus, they may be too detailed and miss a comprehensive overview. This can be considered as a research gap that must be investigated. To close this gap for NPDDP a two-step approach is applied, where the two steps reflect requirement modeling and complexity management framework configuration.

3.4 Requirements

The *classical requirements* of NPPDP are related to criteria like production cost, investment, cycle time, optimal layout, flexibility, and meeting general project goals (time, cost, and quality) (Schady 2008). As shown, besides these classical requirements, it is vital to define the *complexity management related requirement*. They are categorized in three main groups.

Process-related requirements are related to the engineering process execution. Here transparency, modularity, reusability, adaptability, and finally standardization of processes and their corresponding outputs as well as their predictability are relevant.

Interconnectivity-related requirements focus on the information exchange along the engineering process chains. The quality of the information exchange related to correctness, completeness, and appropriateness shall be ensured. Thus, misinterpretation, or extensive retreatment of information shall be prevented along the engineering chain.

Dynamics-related requirements face the dynamics within the engineering chain and its volatility. They include NPPDP monitoring and agile change management.

3.5 Complexity Management Framework

Figure 3.8 illustrates the main parts of a framework for NPPDP complexity management that shall address all characteristics of complexity. As shown earlier, the interaction of and dependencies between the involved engineering steps and their volatility cause high information flow and are the main complexity drivers (MirRashed et al. 2016). These information flows have two mainstreams: information flows within product engineering and information flows within production system engineering. They require a detailed understanding of the engineering chains (that may be based on an appropriate process model) (Gadatsch 2015). In addition, both engineering chains are accompanied by knowledge management activities to ensure effective reuse of engineering data.

As product engineering results in changing product design, change management is required to ensure the transmission of relevant impacts to production system engineering and back. The availability and completeness of product data strongly depend on the number and position of quality gates and product-release strategies defined within the project management as quality assurance mechanisms.

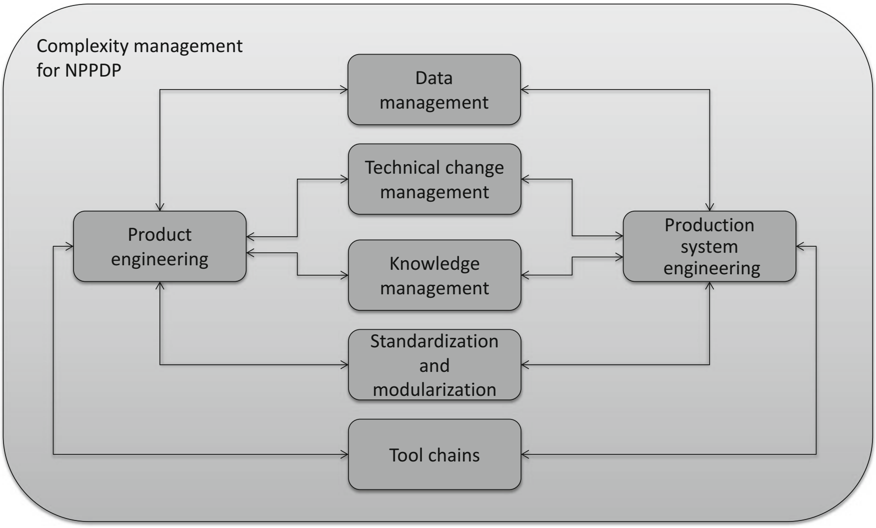

Fig. 3.8 General complexity management framework for NPPDP

The tool chains applied within the engineering processes and their volatility are another complexity driver. Especially the increasing digitalization leads to relevant impacts on engineering quality and efficiency (Biffl et al. 2017).

Finally, standardization and modularization is an important driver in NPPDP. It affects both the modularization and standardization of the product as well as the production system leading to component catalogues to be applied by engineers.

3.5.1 Engineering Processes

Gadatsch (2015) defines a process as a regular repeating activity set that has determined starting and end points. This activity set processes predefined input information to provide output information. There are many methods for modeling engineering processes such as flowcharts, RACI (Responsible, Accountable, Consultedand Informed) charts, activity diagrams, and SIPOC (Supplier, Inputs, Process, Output, Customer) diagrams. These methods provide an appropriate overview of the whole system and the interconnection between system elements. Thus, they help to obtain transparency.

Within the proposed NPPDP complexity management approaches, the first step shall be related to modeling the engineering processes. As the model and the illustration of whole engineering processes in NPPDP must be transparent and understandable to ensure clarity and easy inside, the level of details must be corresponding.

Even if a swim-lane diagram may initially seem appropriate for a large-scale project like NPPDP, where milestones and responsible organizational units can be added to the diagram to increase perception of the whole system, this kind of diagram is only one option. It is up to further research to find appropriate modeling mechanisms for reflecting the necessary information exchange within the engineering chain covering required engineering data quality.

3.5.2 Data Management

Product engineering data and production system engineering data are both main pillars of the NPPDP and main complexity drivers. They must be timely exchanged within NPPDP owing to the gradual development of product and production system variants, simultaneous engineering, and technical changes in the development phase. Incomplete information or time-delayed information could mislead and intensify complexity.

The issue of information management is addressed in many studies. A common approach for information management in NPPDP processes is the use of Product Lifecycle Management (PLM) tools interconnected with the different tools within the engineering tool chain (Sindermann 2014). In the PLM tools, the product data act as core model including direct and indirect relations to process and production system information. Recently PLM data tend to be enriched to overall system engineering models covering product, production process, and production system engineering information (Biffl et al. 2017). An example of such information are product data related to the car body components that include main assembly, subassembly structures, geometries, and joining information as basis for process and for production system engineering.

In multivariant NPPDP used in the automotive industry, the completeness of required engineering information is essential for the work of all production system engineers. Hence, a dedicated product data release strategy is required to manage the complexity coming from the interconnectivity of planning processes. These release strategies are mostly compatible with approaches in the ramp-up process. Therefore, recent ramp-up strategies (Schuh et al. 2015) can be adjusted for product release. In the early phase of NPPDP proper product data release supports to avoid unnecessary complexity in the production system engineering by eliminating uncertainty due to incomplete or time-delayed information. The quality and accuracy of product data help to reduce misunderstandings and increase transparency.

Quality gates (QG) assure the quality of delivered data from product engineering by means of a set of measurable criteria that were initially agreed upon within the complete NPPDP (Richter and Walther 2017). The challenge of defining quality gates (QG) for product data is characterized by three factors: a set of measurable criteria, placing the QG in the proper phase of NPPDP, and the frequency of QG. QG help to identify and correct errors in product data in the early phase and to avoid costly changes later on.

Due to the increasing number of variants handled within NPPDP, quality criteria are increasingly relevant issues within the definition of QG. These quality criteria may range from simple completeness check-ups to detailed reasonability criteria for the consistency of engineering information within the multidisciplinary engineering of an NPPDP. Here, appropriate means for modeling, integration, and evaluation of complex and discipline-crossing consistency rules within PLM systems are required and still not well addressed.

3.5.3 Technical Change Management

According to DIN 69901, change management includes five activities: record, evaluate, decision making, documentation, and implementation of changes. Following the increasing complexity of products and the fast evolution of customer and technology markets, it is almost impossible to avoid technical changes in NPPDP. A research study revealed that approximately 20% of the product engineering and 40% of the production system engineering efforts were dedicated to technical change management (Köhler 2009). As presented in the sections above, the strong interconnectivity of engineering activities within NPPDP requires a detailed change propagation making changes to complexity drivers.

The cost of technical changes, depending on the phase of occurrence, could vary and affect the cost of NPPDP. Therefore, it is very important to distinguish and communicate changes. The faster the change identification and change information propagation process, the more cost-effective is the technical change management. Monitoring and tracing changes in the overall set of engineering information, therefore, provides a reasonable basis. Hence, the engineering data need to be enriched by appropriate data management information covering thinks like version and revision management information, data owner information, etc. This is still an open issue within engineering data management systems.

3.5.4 Knowledge Management

Knowledge management refers to the ability of identifying, collecting, sorting, storing, and retrieving a set of scientific and technical information (Carayannis 2013), which can be reused. Within NPPDP that can cover product and production system data from previous projects, which can be combined with production system component data from suppliers. In the traditional approach, thisinformation is not applied in the early phases of NPDP. The early engagement of this knowledge in NPPDP can reduce complexity.

However, the collection and quick evaluation of such information is a challenging task due to the big information flow (big data), missing structure, and the corresponding IT system (Olsen 2017). Thus, structured information in combination with agile data management shall be considered within the integrated information management system of NPPDP in order to avoid and manage complexity.

3.5.5 Tool Chains

Digital engineering tools are the foundation of NPPDP (Biffl et al. 2017). Providing engineering data in an overall engineering data logistics that extends PLM systems helps to reduce the development time and provides the essential data for the work of engineers within all engineering phases. Especially, the engineering data logistics enables the connection between product engineering and production system engineering (Bracht et al. 2017). Simplifying the communication between product and production system engineering enables the production system engineers to be involved in very early phases of NPPDP, giving bordering conditions also for the product engineering.

NPPDP operate in a more agile manner and engineers analyze numerous scenarios in a very short period by means of simulation. In the automobile industry, an engineer spends approximately 60% of their capacity to obtain information (Reijers and Mendling 2008). Digital engineering tools provide the possibility of perceiving the data in a way that would be suitable for further processing and save the time of engineers for engineering activities.

Nevertheless, these tool chains can only appropriately interact if they all support the interaction with the envisioned engineering data logistics based on appropriate engineering data exchange technologies (Biffl et al. 2017).

3.5.6 Standardization and Modularization

The last part of the framework, like many other approaches in complexity management, recommends the standardization and modularization of the product, production processes, and production systems, especially for multivariant production as in the automotive industry. Using the standard and modular elements in NPPDP generally speeds up the development and ensures the termination of activities within planned time (Reijers and Mendling 2008).

Standardization and modularization approaches reduce the possible variability within the objects to be engineered (product and production system) by enabling the definition of generic system architectures and system components (VDI 2010).

However, standardization and modularization require a modeling methodology for system components, in case of NPPDP components of products and production systems with their interrelation over processes. This modeling methodology shall go beyond currently existing methodologies defined, for example, in PLM tools or ISA 95 standard.

3.6 Summary

Increasing globalization and technological improvement have resulted in a change to customer markets also in the automotive industry. This has a major impact on the joined engineering of products and production system within this industry as it enforces system complexity increase und development time reduction. It can be stated that the joined engineering of products and production system tends to become dynamically complex with three main characteristics of complexity: diversity, connectivity, and uncertainty.

Currently, there is no holistic complexity management framework available applicable for the joined engineering of products and production system within the automotive industry. Thus, this chapter has addressed *Complexity-related Research Questions* (CrRQ) that shall assist the development of such a framework.

The first research question (CrRQ1) has addressed means for complexity management, enabling organizations to deal with the growing complexity within *new product and production system development processes* (NPPDP) while the second one (CrRQ2) has concentrated on requirements to engineering organizations intending to integrate an increased complexity management NPPDP.

To address these questions, Sect. 3.2 collected complexity challenges arising in the joined engineering of products and production systems in the automotive industry within an NPPDP, characterized as dynamic complexity. Section 3.3 reviewed existing complexity management methods and evaluated how they can contribute to a holistic NPPDP complexity management. Section 3.4 discussed requirement groups for such a holistic complexity management. Finally, Sect. 3.5 presented the first ideas for such a framework, which consists of the six main pillars of defining and modeling engineering processes, data management, technical change management, knowledge management, standardization, and modularization, and tool chain management. The modeling of engineering processes provides a clear overview of the NPPDP as a system and creates a better understanding. The combination of product and production system engineering data management and knowledge management supported by appropriate engineering tools helps to resolve the main part of complexity by providing integrated information management. This combination provides transparency and eliminates unnecessary dependencies between two NPPDP engineering activities. Finally, standardization and modularization again reduce dependencies by means of proven and commonly known approaches. All these parts of the framework follow the common approach to avoid, reduce, and manage complexity.

Nevertheless, there are still some challenges to tackle by research and development to make this framework applicable. This chapter has identified the following challenges:

- Providing appropriate modeling mechanisms for engineering chain modeling and analysis reflecting the necessary information exchange within the engineering chain covering required engineering data quality

- Providing modeling, integration, and evaluation means for complex and discipline-crossing consistency rules applicable in multidisciplinary engineering data management systems
- Enhancing multidisciplinary engineering data management systems by appropriate data management information modeling means covering thinks like version and revision management information, data owner information, etc.
- Integrating multidisciplinary engineering data management systems with agile data management
- Providing appropriate engineering data exchange technologies for multidisciplinary engineering data management systems
- Providing modeling methodologies for system components applicable in multidisciplinary engineering data management systems

The subsequent chapters of this book take up most of these challenges and provide means for their solution.

By discussing the named CrRQs, this chapter has contributed to the RQ1a: "What are typical characteristics of engineering processes for long-running software-intensive technical systems?" and RQ1b: "What are requirement areas from engineering processes for long-running software-intensive technical systems that require informatics contributions?" named in Chap. 1 discussing especially challenges related to complexity management.

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