Towards a Methodology to Support the Development of Flexible Company-Specific Engineering Design Processes

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***Abstract*--Engineering design processes are complex systems resulting from complex tasks. While the definition and management of engineering design processes are important tasks, as evidenced by empirical studies, a number of unsolved research questions persists in literature. Within this paper, current research issues identified in a literature review are compared with results from empirical studies in order to triangulate the most pressing research issues. Currently, two interview studies have been conducted with small-to-medium sized enterprises and startups of varying sizes: a case study concerning process development within an engineering department of a global enterprise, and an observation of a workshop to define a new product development process in another global enterprise. As a result, two issues have been concretized: A lack of methodology concerning the development of company-specific standard engineering design processes and a lack of flexibility and adaptability of these standard processes in practice due to different project contexts. Consequently, a first draft for a methodology to support the development of flexible and adaptable engineering design processes has been developed. The methodology combines traditional process-development activities with a bottom-up analysis of project contexts and influencing factors. The methodology currently represents a work in progress and its constituent steps will guide further research activities.**

I. INTRODUCTION

Developing complex, innovative systems in a modern world driven by globalization puts enormous pressure on companies. Never have customers been able to choose from a larger variety of suppliers and, hence, been in a position to demand lower prices, higher quality and more customized products. This in turn pressures companies into decreasing time to market and development costs [15]. Furthermore, in order to keep up with customer demand, modern and innovative products become increasingly complex, spanning multiple disciplines, such as mechatronic products. This trend is continuing, e.g. when observing recent developments such as product-service systems and increased digitization. The endeavor of developing such complex systems results in processes and organizational structures whose complexity often rivals or even overtakes that of the developed system itself [9].

There is a strong case in the literature for the benefits of formal and structured engineering design processes (a.k.a. product development processes). In general, models of engineering design processes support a number of functions within organizations. Among them are the communication between designers, the training of new members of the organization and organizational knowledge management for which they can form the basic structure. However, at the same time, they are also seen as being among the most difficult class of processes to understand and model [36]. Empirical evidence has been published in support of the hypothesis that formal and structured yet also adaptable processes aid in successful engineering design projects in order to finish on time and within cost restraints as well as to fulfill customer satisfaction (cf. [43], [23], [34]).

Within the scope of this paper, primarily knowledge-intensive processes from the domain of engineering design processes (EDP, a.k.a. product development processes or PDP) and approaches to manage and design such processes are considered. These processes differ vastly from regular business processes in their characteristics [45]: Regular business processes are fixed, rigid, and need to be reproducible and 100% checkable. They need to have predictable results and are fully described. Because of the complete description, the possibility of disruptions is low and there is no need for capabilities to react dynamically. On the contrary, engineering design processes are dynamic, creative and chaotic, with iterations and jumps und thus not fully predictable. Their description is not always precise and their constituents, such as concepts, ideas and designs, do not always manifest. Hence, they have a high possibility of disruptions and a need for dynamic reaction capabilities. Besides this characterization, different levels of process models will be distinguished in this paper, as described in section II-A.

II. METHODOLOGY, STRUCTURE & CONTRIBUTION

In this paper, we applied the methodology of triangularization with the objective to create a richer picture and concretize current and relevant research issues associated with the domain of defining, modeling and managing EDPs [12]. In order to achieve this objective, first, an initial literature review has been performed in order to identify the most pressing research issues within this domain. Second, a number of empirical studies has been conducted: Two interview studies, one single-case study and an observation of a process-definition workshop. Afterwards, the collected qualitative data have been analyzed in order to identify current and relevant issues and problems associated with modeling and managing EDPs in practice. By comparing literature and empirical evidence, we then selected the, in our opinion, most relevant research issues and developed a first draft of a methodology in order to address these issues. Hence, in terms of the design research methodology, the first two steps (literature & empirical studies) represent part of the descriptive study I, while the development of the approach represents an initial prescriptive study open to being further detailed in the future [8].

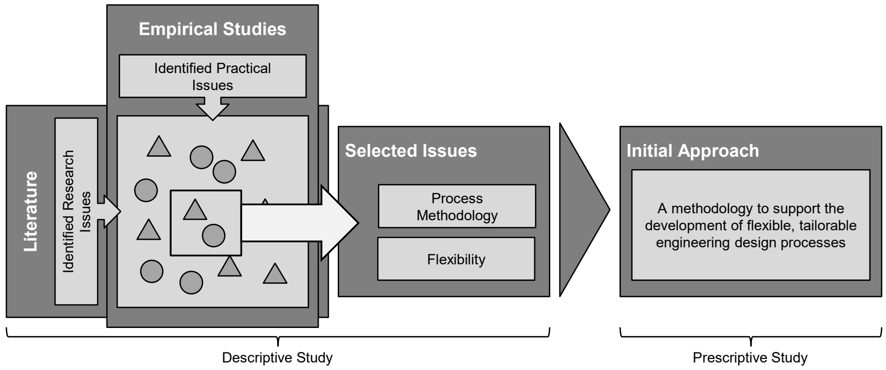

Figure 1 Research methodology

Within the presented context, the scientific contribution of this paper can be summarized as follows:

- First, a number of current issues concerning EDP modeling and management are presented and subsequently triangulated with the current state and issues found as a result of empirical studies: One interview study (5 participants)) with small-to-medium sized enterprises (SMEs) in Germany regarding the development and application of their EDPs, another interview study concerning the process orientation of start-ups in Germany (14 participants), a case study concerning the development of an EDP within a plant engineering company, and an observation of a workshop tasked with developing a new product development process.
- Second, an initial methodology is proposed that follows the objective of addressing selected issues. Specifically, this concerns the development of company-specific flexible, tailorable standard processes. For this, the methodology combines a top-down approach to map and define EDPs with a bottom-up approach based on the analysis of influencing factors from the organizational as well as individual project context. The proposed methodology, however, must currently be categorized as a work in progress. The methodology is intended to lay the foundation to conduct further research and detail the individual steps of the methodology. Also, the methodology will be continuously scrutinized while conducting the research activities outlined in section IV-C. In order to apply and further develop the methodology and its constituent elements, use cases with a number of companies are currently in preparation.

The structure of the remaining paper is as follows: In section III, an overview over the background and theoretical foundation concerning EDPs and process/project management is presented, followed by a selection of research issues currently discussed in section IV. In section V, the structure and results of the empirical studies conducted are presented and issues for further research are subsequently identified. Afterwards, in section VI, the first draft of an approach is presented: A methodology to support the development of flexible, tailorable EDPs. Section VII concludes this paper with a summary, a brief discussion of the methodology and an outlook on further research activities.

III. BACKGROUND AND FUNDAMENTALS

A. Engineering Design Processes: Definition and Classification

EDPs have already been described in the introduction (cf. section I) as being knowledge-intensive processes with certain characteristics distinguishing them from regular business processes. Many approaches from the field of business process management pertain validity for the management of EDPs, however, they are complicated by the differing characteristics of EDPs that need to be considered, such as the complex nature of the product developed, the process and the difficulty to capture these highly interdependent aspects in models. A process can be defined as a set of activities targeted at solving one or a set of similar tasks. The set of activities or constituent sub-processes can be dynamically adapted to a specific task. Hence, processes are virtual objects describing how a task can be solved [45].

Within the scope of this paper, certain levels of processes are further differentiated, from general *design methodologies*, via company-specific *standard processes* and *project processes* to *actual processes (*cf. *Figure 2).*

General design methodologies are e.g. the “three cycles” [19], VDI 2221 [35], the “Munich procedural model” [32], the generic stage-gate process [14], or agile frameworks, such as SCRUM [39]. On the one hand, general design methodologies have been developed for individual disciplines (such as mechanics, electronics and software), but also in the form of interdisciplinary design methodologies, e.g. for the development of mechatronic products, such as VDI 2206 [18], or Systems Engineering [24]. Design methodologies generally possess a very high level of abstraction and need to be adapted to a specific company’s needs and boundary conditions [21]. There are numerous design methodologies; for a further overview and comparison cf. e.g. [16] or [40].

The next level of processes are company-specific standard processes that represent the high-level path engineering design should follow within an individual company [36].

They include a number of different elements, such as specific phases and milestones, organizational departments and important documents that need to be created during the engineering design process. These elements are interlinked, creating networks of tasks, tools, documents, IT systems and agents. Individual processes, such as the EDP, are embedded within a company's process architecture, along with a number of other processes (e.g. procurement, marketing, sales) [6]. The language necessary in order to model EDPs, i.e. describing the aforementioned interlinked networks, is defined in corresponding meta-models, containing elements, relationships, and attributes for both (cf. [11], [28]).

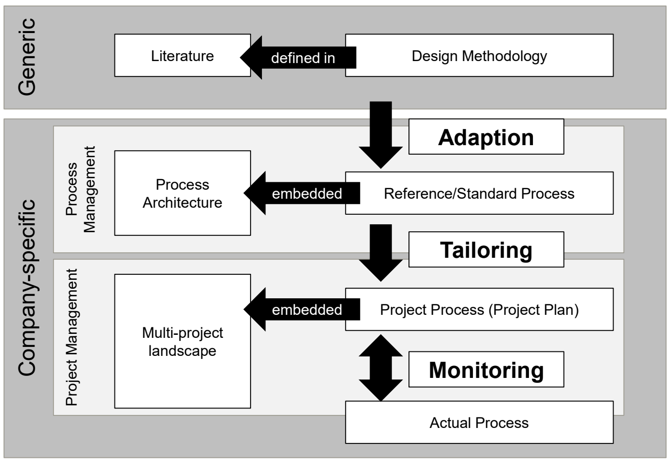

Figure 2 – Levels of engineering design processes

Following the standard, processes are specifically tailored project processes ("set of activities that actually happen", [36]). According to [45], "a project is a process with an actual and real task to address". A project, hence, instantiates a standard process by defining its starting conditions, such as the schedule, budget, resources, and requirements. Hence, tailoring standard processes to project processes is a reoccurring activity in project management. In reality, process-relevant information resides in various separate repositories and models, e.g. Gantt Charts, work breakdown-structures, databases for lessons learned, risk management plans and role descriptions. These models and repositories regularly become unsynchronized over the course of a project due to them being developed and maintained by the different stakeholders of a project, requiring an effort to synchronize them [10]. An extensive number of modeling approaches exists, fulfilling different purposes. For an overview, refer to [9], [10] or [3].

The actual process of a project, or rather its progress, needs to be continuously monitored and compared to the project plan, and corrective actions need to be taken, if necessary (cf. Section III-B).

B. *Process Management and Project Management*

Within the context of this paper and in respect to the aforementioned classification of processes, we further differentiate process management from project management, with a clear interface defined between both.

In business process management, process management includes many aspects; among others are scheduling, communication, and resource management [6]. Reference [41] classifies process management activities into the group's modeling & documentation, analysis & simulation, monitoring & automatization, export of knowledge, and managing & archiving models. As shown in section I, business processes are executed quite often, which is supported by workflow management systems [41]. On the contrary, engineering design is typically conducted in the form of projects: Unique and often infrequent endeavors in which something novel or innovative is done once and not repetitively such as in business processes. "Project management is the application of knowledge, skills, tools and techniques to project activities to meet the project requirements" [1]. Within this context, project management activities extend to five groups: Initiating, planning, executing, monitoring/controlling and closing projects. The unique focus of project management is formed by the specific project's goals, resources and schedules [1]. Hence, we define process management as being concerned with the development and maintenance of standard processes and operating procedures of a company, and project management being concerned with managing specific instantiations of these company processes. The interface between process and project management, hence, consists of the handover and instantiation of the process, on the one hand, and the feedback of lessons learned and project experiences into the standard process on the other hand. While a process focusses more on the individual activities and their relationships within the context of a process architecture, a project is enriched with further context and organizational aspects [38]. In order to manage complex engineering design projects, the different views on a project's process (or rather, process networks) mentioned in section III-A are necessary, such as Gantt charts or work breakdown structures [9].

In order to effectively plan and model design processes, former project experience is necessary. Data gathering about such complex and often very infrequent projects becomes an issue, and generally a lot of uncertainty from different sources impacts the design process [17]. Design processes are further influenced by constraints, such as from the product itself [42]. This results in a lot of ambiguity when modeling EDPs, based on a lack of knowledge relating to the conclusion of process elements, which can only be reduced over time by observing a number of actual design processes [36].

C. *Process tailoring*

One of the constituent elements of the interface between process management and project management mentioned in section III-B is the activity of process tailoring. Process tailoring is generally defined as the activity of "adjusting the definition and/or particularizing the terms of a general description to an alternate environment" [22]. In the literature, this can mean two things: Tailoring design methodologies to organizational contexts (cf. [21], in Figure 2 and within the context of this paper called *adaptation*) and tailoring company-specific standard processes for specific project contexts. The latter of these defines the use of the word tailoring in the context of this paper. Recent research on process tailoring has been done predominantly in the domain of software engineering (cf. e.g. [29]). In order to tailor standard processes to projects, certain criteria need to be considered, such as team size, available knowledge and the product in question [27].

IV. ISSUES REGARDING EDP MODELING & MANAGEMENT IN LITERATURE

EDPs are a heavily discussed subject in literature. When investigating this area of literature, it becomes evident that there are a number of unresolved issues regarding the definition, modeling and management of EDPs. The listing in this paper is not meant to be a complete enumeration; instead it intends to provide an overview of current and pressing issues. Among the issues mentioned in literature are:

- A lack of guidelines and implementation support for company-specific process models. This has been deduced through conducting an analysis and comparison of existing high-level design methodologies by [16]. It implies that there is a lack of support for adaptation in order to tailor high-level design methodologies to specific companies. This implication is further corroborated by [44], which mentions a "need for an improved PDP design method", which is "real and immediate". The issue is that EDPs are often "based on history, mimicry, ideology, or vague comparison of process shapes and diagrams".
- Process architectures and, especially, the interfaces between individual processes are not sufficiently considered in current approaches [31]. While business process architectures are generally considered a topic within the domain of business process management, such processes do also have interfaces and connections with EDPs, e.g. procurement, sales, or marketing. Some partial aspects of EDPs may also be standardized, such as testing, which further contributes to the complexity in managing them. The consideration of process architecture frameworks has also found recent uptake in the domain of EDP (cf. [9])
- Based on a comparison of existing process planning methodologies, [5] identified a lack of methods supporting the definition ("synthesis") of new processes.
- The tailoring of a company-specific standard process to project-specific requirements is, while unquestionably important, not well supported. Instead of having a clear understanding and support for repeatable and traceable tailoring activities, tailoring is often done by project managers on an ad-hoc basis instead [29]. Additionally, the required degree of formality of the process tailoring activity is an issue discussed in literature. A "complete and general framework for process tailoring" is currently lacking, since existing approaches have been developed for very specific environments and the needs and constraints of SMEs have not been adequately considered [37].
- In literature, only few approaches for structured process improvement exist, in contrary to the number of process modeling approaches available. Moreover, the approaches are complicated and often only address business processes of sequential nature [46].
- Among the top ten issues and challenges identified in a study conducted by [25] concerning process modeling are the process modeling methodology and its ease of use, support for collaborative modeling efforts, the correct level of detail of process models, the value of process modeling for companies, and the governance of process modeling efforts.
- Concerning the modeling and management of EDPs specifically, [20] identified a number of pressing research issues in modeling and managing EDPs. The issues have been identified in workshops conducted within an active international research community[1]. Among others, within the top 10 research topics range: the capturing of a design processes rationale, organizing knowledge about the process, product and relevant relationships, as well as the coupling of discipline-specific design processes.

V. EMPIRICAL STUDIES

Within this section the qualitative empirical studies concerning issues in process modeling and management in German SMEs are presented. First, an overview is given over the structure and content of the studies. Subsection B contains the results from the studies, after which implications for further research are drawn in subsection C. Due to space constraints, the full questionnaires are not included. However, all studies were guided by three basic questions:

- What is the status concerning the process orientation (formalization and management) within the individual companies‘ engineering departments?
- How do companies develop their EDPs? Are specific methodologies applied in practice?
- How do companies manage their processes in practice, i.e. what methods and tools do they apply?

A. Overview over conducted studies

In order to compare the issues mentioned in the literature (cf. section 1 B) to managerial practice, we have conducted qualitative empirical studies. In total, we draw conclusions from four different studies (There has been no overlap between the individual studies in terms of the companies questioned or observed. Per the companies' requests, all data has been anonymized):

[1] Special Interest Group Modeling and Managing of Engineering Processes - https://www.designsociety.org/mmep-sig

TABLE 1 – COMPANY DESCRIPTION FOR SME STUDY (STUDY 1)

Company		1-A	1-B	1-C	1-D	1-E
Industry		Plant Engineering	Appliances	Tier 1 mechatronic system supplier	Appliances	Appliances
Market		BSB	B2B/B2C	B2B	B2B	B2C / B2B
Scope of Investigation		Entire Development	Electronics Dev.	Entire Development	Entire Development	Electronics & Drive Dev.
Size (Development)		~120	~3100	~70	~ 10	~ 60 (Electronics & Drives)
Overall Process formalization (Standard Process)		Low (Single high-level process)	High (multiple processes for engineering design)	High (single process for engineering design)	None	Low (Single high-level process)
	Form of process formalization	Office documents (Visio Graphs)	Office documents (presentations), specialized software	Graphics + textual description (Office documents)	None	Office documents (presentations)
	Process models used	Flowchart (semi-formal, BPMN-like)	Flowcharts (Informal)	Flowcharts (semi-formal, BPMN-like)	None	None
	Software support for process management	No (standard office software)	Yes (specialized software)	No (standard office software)	No	No
Discipline-Specific Processes		Yes (Non-documented)	Yes (partly documented and formalized)	No (single EDP-Model)	No	Yes (non-formalized)
Methodology for Process Development		No	N.A.	No	No	No
Design Methodology		Stage-Gate	Stage-Gate	Stage-Gate & V-Model	None	Stage-Gate & V-Model
Application of the process in daily practice		Very Low	High (experience-based process tailoring)	High (experience-based process tailoring)	None	Medium (mainly Gates and prototypes)

The first interview study (*study 1*) was conducted within the scope of an ongoing research project among a group of well-established SMEs, all with a background in mechatronic product development (see Table 1). The intent was to compare the process orientation of all participants in order to derive the potential for improvement for the development process of mechatronic products. The initial interviews were of a semi-structured nature in order to allow for a better adaptation of the content to the individual companies' circumstances. Follow-up interviews have been conducted via telephone.

A second interview study (*study 2*) was conducted within German start-up companies using a structured interview guideline. The interview study is ongoing at the time of writing; so far 14 companies have been interviewed in total (Table 2). The intention of the study was to investigate whether start-ups apply formal processes at all, and determine what design methodology they use. In the case a start-up does indeed apply a formal process, the development background and rationale of the process was further investigated.

TABLE 2 – COMPANY DESCRIPTION FOR START-UP STUDY

Company	2-A	2-B	2-C	2-D	2-E	2-F	2-G	2-H	2-I	2-J	2-K	2-L	2-M	2-N
Industry	Home Appliance	Software	Vehicle Tracking	Engineering design office (Wind Energy)	Rescue Equipment	Crime scene evidence processing	Machinery control technology	Engineering design office	Convertible building facades	Standardized building elements	Fibre-optical sensors	Fitness sensors	Fitness sensors	Wind Energy
Disci-plines	M/ EE/ SW	SW	EE/SW/Ser-vice	M/EE/ SW	M	M/ EE/ SW	M/ EE/ SW	M/ EE/ SW	M/ Civil. Eng.	Civil Eng.	M/ EE/ SW	M/ EE/ SW	M/ EE/ SW	M/ EE/ SW
Size (dev.)	1	30	2	6	4	4	8	5	3	2	16	8	8	7
Process formali-zation	○	○	◐[1]	○	◐	●	◐	◐	○	◐	●	○	○	◐
Metho-dology	-	SCRUM	-	-	SPAL-TEN[2]	ISO 9001	SCRUM	SCRUM	-	-	ISO 9000	SCRUM	-	SPAL-TEN

[1] Generation of formal documents, e.g. requirements list, project documentation; [2] SPALTEN Procedural model, cf. [2]

Besides these two interview studies, a single-case study was conducted in a large-scale plant engineering company in order to gain a better understanding of the realization and potential pitfalls of process design in a specific case in practice. Within this case study, a small division of the company (development of chemical storage tanks) was tasked with developing an engineering process that had to be integrated within the overall engineering design process. The case study was chosen because of the clearly defined scope of the process and the initial boundary conditions of the process definition project: The company is ISO9001 certified and uses an integrated management system, which includes a central repository for the company's process architecture, and the engineers were tasked with developing the process themselves. From a methodological perspective, the study is of a single-case design and considers the EDP definition and modeling project as its (single-)unit of analysis. It was chosen because, based on the experiences made before and the observed context, it is a very common case [47]. Since the researcher could influence the methods and methodologies applied to develop the engineering process in the further course of the case study (to a limited degree), it is similar to action research [4].

Lastly, we observed a workshop within a SME (OEM, mobility industry) specifically tasked with the design of an EDP for the development of new products. The workshop was conducted with 25 people attending over 2 days and was not influenced by the researchers. As basis for the discussion, a former version of the process developed by a consulting agency was used. This process was developed about 5 years prior, but never used in practice.

The results of the empirical studies are presented in the next section. They mostly represent problems and challenges concerning the development, modeling and management of EDPs we encountered in practice.

B. *Results of the empirical studies*

The presentation of the results follows the same structure as the overview of the empirical studies in section I.-A.

Study 1

To summarize, all of the investigated companies in *study 1* were active in defining and establishing formal EDPs, with varying degrees of progress and success. Consequently, the formalization of their EDPs (or rather, their descriptions/models of them) also differed. Further, the companies described various issues concerning their EPDs and their formalization efforts:

Company 1-A has undertaken prior activities in order to model and implement a formal EDP that failed. The documentation of this process is still available within the company, but is not applied in daily practice. This led to the existence of different "mental models" of the current process within the company, and, hence, a different understanding of the activities involved in the process. The company has since made new efforts to model the current EDP. In this case, we had the chance to interview the engineer responsible for mapping and modeling the current EDP. No formal project existed to conduct these activities. The engineer in question had limited former experience with EDP modeling. For the modeling, a business-process modeling tool was used, which uses a language similar to the business process modeling notation (BPMN). He specifically called the development of the process model "complex", especially in regard to modeling the necessary flexibility and level of detail, the iterations necessary within the process and the linkage to other processes. During the time since the first interviews (approx. 6 months), no further effort was made to implement the process. On the contrary, new developments within the company's organizational structure further delayed the endeavor and posed new challenges, due to partial restructuring. It stands to reason that the low repetition in projects and the long product lifecycle in the company's industrial sector is a contributing factor to low process orientation.

Company 1-B faces challenges from development activities spread out over a large number of sites and product divisions. A uniform EDP for all sites has existed since the early 2000's. A large amount of development activities accounts for the adaptation of existing designs and development of product variants. As the only company interviewed in the study, a formal design process for electronics development has been defined and synchronized with the overall EDP. Project-specific tailoring of the standard process is recognized as an important activity and done by the individual project leaders. Their decisions concerning process tailoring (e.g. omission of certain methods and documents) are documented. However, upfront support for the tailoring-activity is limited.

The head of R&D of company 1-C mentioned that their highly formalized EDP ("one fits all") creates a problem, since it does not allow a sometimes necessary, earlier (i.e. flexible) integration of software development than currently defined in the EDP. Also, milestone releases become more difficult as soon as software is involved. Furthermore, the process itself is based on two different design methodologies, which seem to have been integrated: The V-Model[2] and a generic Stage-Gate Process (cf. [13]). This complicates the textual documentation of the process since both paradigms are described. Further, the company struggles to include a more systemic perspective (i.e. interdisciplinary system modeling during concept development) of their products into the design process because of resource restrictions. Hence, it is faced with the issue of a more efficient use of the existing resources within the process in order to address this problem. The company is, furthermore, currently experimenting with the SCRUM methodology for software application development.

[2] While many variants of the V-Model exist, the company documentation specifically references the V-Model 97 (cf. [26])

Company 1-D currently has no form of formalized EDP. However, the company is currently growing fast and has recognized the need for a formalized and documented EDP. The company has a strong background in electronics development and, consequently, needs to integrate external engineering offices when developing mechatronic systems. Development projects are triggered internally as well as externally. Thus, it is heavily affected by external influences due to a variety of different possible stakeholders that follow their own processes (creating process interfaces) and with whom, consequently, communication is often problematic. Additionally, the internal organizational structure is also complex, with the company being part of a larger conglomerate.

Company 1-E has only a superficially formalized process but has firmly established milestones and product maturity levels (e.g. "functional prototype") with which it tracks progress. The individual disciplines have different degrees of process formalization themselves, with software describing activities in great detail and mechanical development working more from experience and implicit knowledge. The interfaces between the different discipline-specific processes are defined within the milestones and maturity levels. The subject matter experts from the company admitted that in theory there is more process documentation available, but it is hard to find and access within the company's systems. They also attributed a lot of current issues to difficulties concerning process implementation, e.g. by addressing all relevant stakeholders. Although company 1-E, like company 1-D is a volume producer of appliances with comparatively short product lifecycles, the less pronounced process orientation than in company 1-D is noticeable.

The subject matter experts from company 1-B and 1-C explicitly described the EDP as a "map" that serves to establish the boundary conditions for the project specific processes. However, while in a concluding workshop, all attending experts agreed that EDPs need to be adapted to a company's and project's requirements (such as e.g. different product divisions within a company); there was no discernible method applied to support the tailoring of the standard processes for different company-specific and project-specific boundary conditions.

Study 2

Study 2 investigated the process orientation in start-up companies in Germany. It showed a very diverse picture, which can be attributed to the very nature of start-ups: They are mostly driven by an initial, single idea that needs to be fleshed out. This takes priority over other managerial aspects such as process and project management. As some interview partners mentioned, due to this context, there is only a limited number of repeatable steps (if any) that merits the definition of processes early on. A common topic among the start-ups interviewed is the propensity towards agile methodologies, such as SCRUM, also for mechanical engineering (mentioned by 5 interview partners). However, two interview partners (2-H and 2-N) also mentioned that they faced issues with SCRUM as soon as larger projects and interdisciplinary aspects came into play, on the one hand, due to the involvement of mechanical engineering, and, on the other hand, due to efficient communication with the customer about his requirements. This fact is corroborated by [7]. Two companies used a design methodology developed by the Karlsruhe Institute of Technology as a basis (SPALTEN-Model, cf. [2]). Another form of input is the mimicry of existing EDPs from larger companies, or the purchase of external consultancy services.

Among the reasons for defining an EDP are a number of external drivers. Investors, customers and the general need for certification (e.g. ISO 9001) were mentioned by 5 interview partners as main drivers for EDP definition. Company 2-K is just in the process of creating a more useful description of their process that can be used for future improvement. The main internal driver mentioned is the increase in personnel involved in product development and the need to manage and coordinate the necessary activities.

Further challenges in the EDP have been attributed to the late phases (2-N): This contains the documentation of the project and the continuous improvement of the associated EDP, due to a lack of structure within the documentation as well as the fact that projects follow each other without much pause for reflection. Also, the individual projects vary highly, e.g. in terms of the percentage of constituent disciplines involved: Projects with a high amount of mechanical engineering are different when compared to projects that mostly concern the development of electronic components or plain software.

Case study

When faced with the task of defining an EDP, the engineers in the *case study* quickly realized that they did not have any means of support available to map and define their own process. A central process management department does exist, but this department only takes over the final modeling efforts when the developed process is already complete for integration in the company's overall EDP. The process in question needs to be highly flexible in order to react to different internal and external influences, such as varying stakeholders. These might have different requirements regarding the process, e.g. different points of delivery of the product (delivery of a concept vs. delivery of a complete plant). Also, another problem is the potentially long time for process completion, which can result in information- and knowledge-deterioration over time concerning the initial concept. This was attributed to an insufficient degree of formalization of the process because e.g. necessary documents and repositories to be created and used have not been defined before. As part of the case study, a literature review has been conducted in order to identify approaches that would support the mapping and modeling of knowledge-intensive EDP. However, the literature review revealed a surprising lack of support in this field. To address this issue, methods from business process management have, consequently, been investigated and adapted in order to support the efforts. Appropriate workshops and interviews have been planned and conducted in order to map the current process. However, there was considerable uncertainty about the most effective and efficient sequence in which these workshops and interviews should be conducted. The case study is ongoing at the time of writing.

Workshop Observations

Lastly, we observed a workshop within a SME specifically tasked with the design of an EDP for the development of new products. This workshop was conducted with 25 people attending over two days. As basis for the discussion, a former version of the process was used, developed by a consulting agency. This process was developed about 5 years prior but never used. During the workshop, three groups were formed, discussing the process in terms of applicability and responsibility of the individual activities from different perspectives (project management, engineering/testing and quality/manufacturing). It was realized that the presented process could not represent all eventualities that might occur when conducting different projects. Furthermore, there was a lack of shared understanding concerning common concepts such as the definition of prototype stages. Hence, further difficulties arose since there was a lack of awareness as to what other groups' requirements for the process might be, slowing down the overall progress and diminishing the eventual result of the workshop. The objective, scope and integration of the overall process within the company's process architecture were not fully defined. Thus, it remained unclear for a number of participants when the process should be applied and what it needs to entail. Eventually, after the two-day workshop, a high-level process was defined, consisting of generic phases (such as "concept development") and a tentative definition of milestones, where e.g. the status of prototypes has been generically defined.

C. Implications for research

As evidenced by the previous section, the general issues identified in the literature (section IV) are largely corroborated by the experiences from practice. Therefore, we draw the following conclusions concerning issues related to the development and management of EDPs:

First and foremost, we identified a *lack of methodology* concerning certain activities, such as mapping, defining and modeling company-specific EDPs in practice. This is complicated by a number of factors: For example, process-related activities do not get the attention necessary (e.g. in terms of resources). Furthermore, such endeavors take a long time and are of an iterative nature, hence, over the course of that time, knowledge drain, in the form of changing roles and individuals, is obvious. Also, the usefulness of EDP models is often not perceived as such in practice. The distinction between process models representing the current and desired state is also not always respected. A prominent pattern we identified is the following: Single individuals or a group define and model an EDP, which represents a mixture of current practices and the desired state. The process model is then initially introduced and tested in pilot projects, often facing resistance from other stakeholders (e.g. due to the mix of current and desired state) and a lack of flexibility due to different project environments which have not been considered at the outset of the project. Hence, we identified a *second* issue: The developed EDP models do not offer the *flexibility* needed for planning and executing engineering design projects with different boundary conditions, i.e. the "tailorability" of EDPs is insufficient and the tailoring activity is insufficiently supported. While highly flexible approaches, such as agile methodologies do work well for software engineering and within the confines of smaller and contained organizational units (e.g. startups or secluded teams), they quickly face limitations when applied to larger companies in an interdisciplinary context, due to more complex organizational and process structures. In the context of larger projects, project managers instead should be made aware of the available possibilities of tailoring the company-specific EDP available within the confines of the process definition in the company, in order to react to expected or unexpected influences.

VI. DISCUSSION AND PROPOSITION OF A METHODOLOGY FOR EDP DESIGN

A. Overview: A Methodology to design flexible and adaptable EDPs

Extrapolating from the issues mentioned earlier, we propose the development of a methodology specifically designed to the requirements posed by the development of usable interdisciplinary, flexible, and adaptable EDPs. We derive the need for such a methodology based, on the one hand, on the importance of EDPs in practice as artifacts supporting the efforts of coordination, communication, continuous improvement, and knowledge management, and, on the other hand, due to the empirically identified deficits concerning the development and handling of EDPs in companies. As we have investigated in the empirical studies, approaches from the field of business process management are often applied in the context of EDP. While these approaches surely yield results, they also often result in inflexible and, over time, unwieldly processes. Hence, in this case tailoring a proposed methodology specifically needs to address aspects from the later phases in the process lifecycle. This is expected to further bridge the gap from process to project management, and improve the management of EDPs in practice. The methodology needs to be supported by the appropriate methods and tools, a point that will be addressed in further research. Such methods are e.g. a classification scheme for engineering design projects. The currently envisioned methodology is presented in Figure 3. The proposed methodology extends traditional "top-down" process definition methodologies by applying a "bottom-up" analysis of project characteristics, project processes and influencing factors.

Hence, the objective of the methodology is to support the identification and assessment of organizational as well as project-related boundary conditions and influencing factors. These are subsequently used in order to identify possibilities as well as limitations for subsequent project-specific tailoring of the standard EDP, i.e. degrees of freedom and limitations for tailoring. The elicited and subsequently formalized (e.g. in the form of tailoring rules) additional knowledge can then be used to support a project manager in tailoring the EDP to specific needs. Due to the complex nature of engineering design projects and the need for dynamic reaction capabilities, a fully automated software to do this seems undesirable. Instead, the support should help prepare the decision-making of a project manager by making available options more transparent and enable him to "navigate" the solution space available for process tailoring.

To summarize, the application of the methodology should provide project and process managers with an increased understanding concerning process flexibility and tailoring options, help identify measures that can be taken in order to tailor interdisciplinary EDP and formalize this knowledge, as well as support the evaluation of the flexibility an EDP offers.

The methodology hence combines the traditional "top-down"-approach of process definition and modeling with a retrospective "bottom-up" analysis approach focused on organizational and project-specific boundary conditions. In the following section, the constituent elements of the methodology will be explained in more detail. Accordingly, a research agenda will be developed in order to flesh out the methodology.

B. Necessary constituent elements and derived research agenda

For the general methodology as well as some methods that will be used as a part of it (e.g. workshops, interviews etc.), we can draw from approaches previously developed for the development of business processes (e.g. [6]). However, these approaches need to be updated and adapted to support the development of flexible EDPs. Consequently, certain steps need to be included in order to address aspects such as the project-nature of engineering design work. The individual steps of the proposed methodology will be further detailed next.

Step 1 - Preparation

The first step serves as preparation for the rest of the methodology. Hence, first the system border, i.e. the process or process phase (Planning, Concept Development,

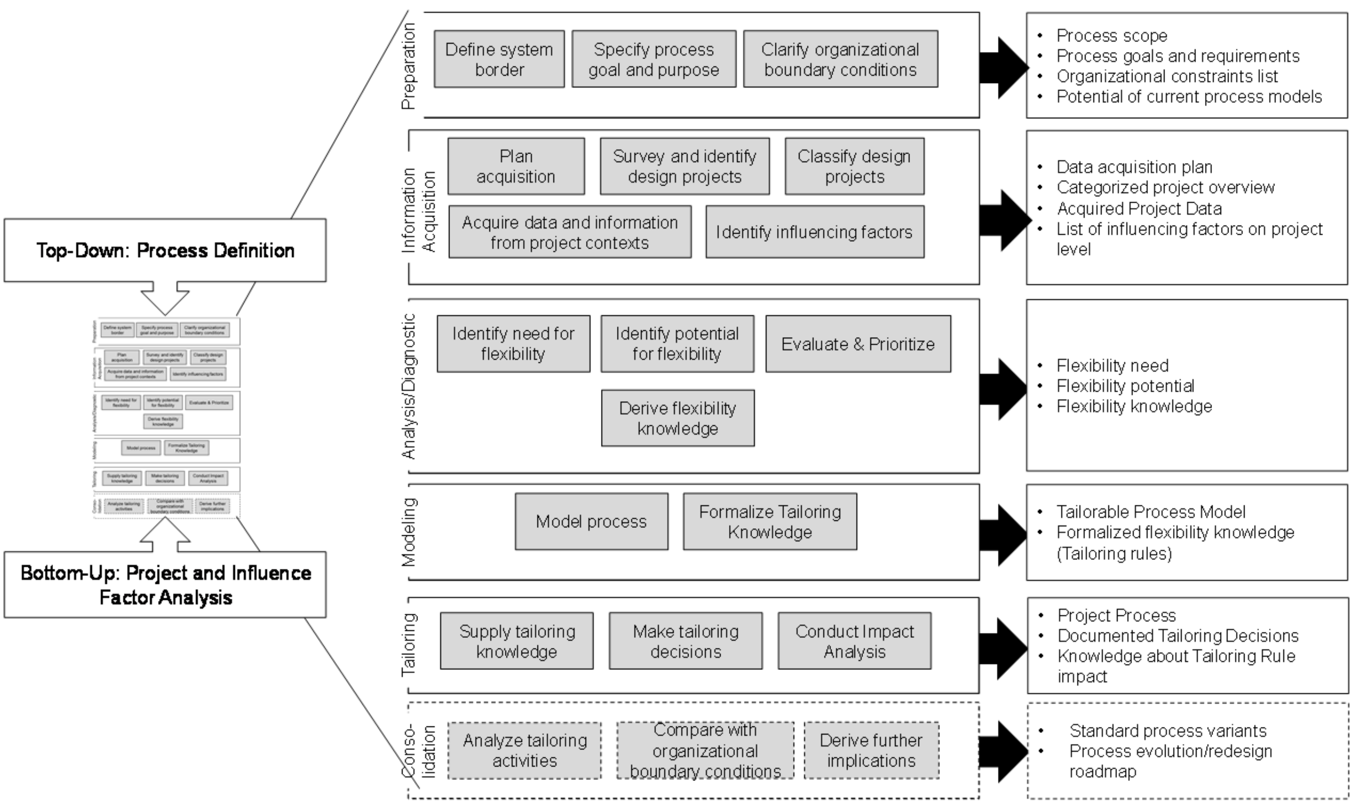

Figure 3 Overview over methodology and intended outcomes

Embodiment Design etc.) intended for further analysis and modeling, is defined. Also, the intended purpose and goal of the process to be developed needs to be specified. Based on this, requirements are derived that serve as input for further steps. This could, for example, entail the identification of critical elements in the process meta-model to be further investigated in the next step, such as documents, individuals, activities, etc. Also, the organizational boundary conditions need to be clarified, e.g. what the organizational structure (disciplines and departments involved, etc.) or the companies remaining process architecture look like, or what industrial sector the organization operates in (resulting in different norms and standards to be followed), in order to identify fixed points (e.g. interfaces between processes) for the EDP. Based on these initial assessments and the resulting meta-information, the subsequent steps of the proposed methodology can be adapted to suit a company's requirements, e.g. based on the project data necessary and available. In order to conduct this preparatory step, a questionnaire will be prepared. The possibility of a "tailorability maturity model" for existing processes will also be investigated.

Step 2 - Information acquisition

The next step after preparation concerns the acquisition of information and the identification of defining influencing factors on organizational and project-level.

The acquisition of the necessary project information needs to be planned in order to ensure its effectiveness and efficiency, since relevant data is often distributed in different systems within the company (e.g. by comparing the quality of the available project data with the effort necessary to acquire it). To support this, an appropriate method needs to be developed in order to methodically fill the elements, relationships and attributes of the EDP meta-model with adequate data. In order to do this, approaches from the domain of structural complexity management will be investigated (cf. [33]). The first step of the actual acquisition is to generate an overview of current and completed projects within the scope set in the preparation step. The projects are then categorized according to their project characteristics (e.g. innovativeness, involved risk, stakeholders, and defining boundary conditions) in order to identify average projects as well as outliers and to enable process designers to choose the most relevant projects to be considered next in order to reduce effort. The criteria for relevance can, for example, be derived from the process goal defined in step 1, e.g. by defining a process for projects with a very high degree of innovativeness. To support this, a list of generic project characteristics needs to be compiled first. The next step is then to acquire more detailed information about the identified projects, according to the scope set in step 1, such as documents generated, activities conducted, individuals involved, schedules, critical decisions, project changes, etc. in order to allow a comparison of different projects (or rather, project-level processes). In order to perform this activity, existing methods to acquire project information, e.g. from the domain of data mining, need to be investigated.

In parallel, the identification and classification of influencing factors with impact on the EDP is necessary. Influencing factors can be internal or external to the organization in question. In order to conduct a structured identification of external influencing factors, the context model developed by [30] can be applied, which considers factors from the domains technology/knowledge, socio economics, politics/legislation and resources. For project-specific influencing factors, [27] have synthesized a list of "tailoring criteria" for software projects. For this task in step 2, it is important to further consolidate the process-influencing factors originating from the different levels (cf. Figure 2), concretize the existing influencing factors (e.g. through clustering and hierarchization) and make them applicable in practice, e.g. through the development of checklists or questionnaires. The result is a reusable list of types of influencing factors with classification criteria that can be applied in practice, support companies in identifying them and, subsequently, reduce uncertainty concerning the impact of influencing factors on the EDP.

Step 3 - Analysis/Diagnostics

Within the third step of the methodology, on the one hand, the need for flexibility is derived from the categorized influencing factors (e.g. different documents for different project types, such as simplified requirements documents for variant development as compared to extensive requirements documents for platform development). On the other hand, the potential for flexibility is derived from the current state, i.e. which justified differences between different projects do exist? To pick up the previous example, different variants of the same basic requirements document might exist due to a reason, e.g. because of different risk profiles of projects. This step aims at retrospectively identifying such discrepancies between projects. Another important factor is also the frequency with which certain identified project types are conducted within the company, in order to prioritize the associated efforts.

Both perspectives are subsequently compared and evaluated in terms of where planned flexibility within the EDP is desired or whether further process standardization is more beneficial. The derived knowledge is further formalized with the intent of using and reusing it in the future, e.g. in the form of rules.

Step 4 - Modeling

Within the modeling step, the standard EDP of the company is being modeled or adapted based on the findings of the previous steps. Further, the identified tailoring knowledge is modeled, e.g. in the form of rules (If … then …) and integrated in or linked with the model of the standard process. In order to achieve this step as well as the previous one, a thorough understanding of the concept of flexibility within EDPs has to be developed and conceptualized in a meta-model. Therefore, based on a thorough literature review, existing tailoring models will be analyzed and adapted to the domain of interdisciplinary engineering design. It is further important to investigate existing process modeling techniques applied in the domain of EDP management in order to derive a meta-model with the extended capability to accommodate the tailoring perspective. Extensive work has previously been done on the formulation of EDP meta-models, as evidenced by e.g. [28] and [11].

Step 5 - Tailoring

This step addresses the actual tailoring of a standard process into a project-specific process conducted by the individual responsible for carrying it out, e.g. the project manager. Within this step, the project manager is supplied with the identified, formalized, and documented tailoring knowledge. He or she is thus able to make informed decisions about the available and necessary tailoring options, conduct adequate tailoring operations, and document them in turn for accountability and traceability. This is especially important since more than one tailoring operation may be applicable in a certain context and trade-off considerations need to be made, e.g. the decision to omit the creation of certain documents or to include more resources in order to finish a project in time. This enables the further analysis and refinement of the tailoring rules, such as thorough analysis of the frequency with which tailoring rules are applied. Through such a feedback loop and the added transparency due to the documentation of tailoring decisions, the continuous learning process should be improved.

To achieve this step, a form to consistently document and present the identified tailoring knowledge (i.e. the tailoring rules) is necessary, e.g. in the form of lists or – preferably – a database system.

Step 6 - Consolidation

The last element of the methodology represents the optional further consolidation of the identified flexibility needs on the level of organizational standard processes. This supports a more long-term perspective on the EDP, enabling roadmapping and planning future changes.

This step uses the output prepared by the preceding steps: Based on the organizational and project-level influencing factors, stable conditions can be identified and consolidated to form the basis for the definition of specific EDP variants for different product departments or company sites or other often-repeating boundary conditions. Another possibility is the definition of enclosed process modules based on frequently recurring combinations that can then be used to tailor project-specific processes with reduced effort.

VII. CONCLUSION

A. Summary

As can be seen from the literature review and the empirical studies, the design of EDPs is not an easy task. Developing and introducing processes takes a long time and the processes need to be implemented and evaluated in a number of projects in order to work out problems before they can be deemed fully implemented. Also, EDPs in practice are subject to frequent changes and redesigns. Due to the requirements posed, they need to support communication within an organization but also be flexible in order to react to different challenges. Modern approaches such as agile methodologies tend to work only in smaller organizations and face limitations when applied in larger and more complex environments. Standard EDPs within organizations need to be tailored to project-specific boundary conditions on a regular basis, yet this activity is largely unsupported in practice, as evidenced by literature and empirical studies presented in this paper. Since EDP-specific approaches are lacking, companies rely on approaches from the field of business process management which, while yielding results, nonetheless, are not fully appropriate for EDP development, due to the requirements of engineering design, such as its highly iterative and complex nature as well as the need to instantiate specific projects with varying boundary conditions.

In order to solve these issues, in this paper we propose a methodology to support the definition of company-specific flexible and adaptive (i.e. tailorable) EDP. The proposed methodology combines traditional top-down process development with a bottom-up analysis of current and past engineering design projects within a company. It takes into account the necessary systematic identification of organizational as well as project-specific influencing factors that impact an organization’s EDP on standard- and project-specific levels. That way it contributes to the identification of needs and possibilities (i.e. degrees of freedom and limitations) for process flexibility and adaptivity within the context of project-specific tailoring. The methodology contributes to a better understanding and more transparency concerning process flexibility, adaptability and tailoring within a company. This in turn enables more conscious and better informed decision-making at the hand of project managers. This should result in a faster and more consistent reactive capability when conducting tailoring activities and further enable a continuous learning process. With the increased transparency and more structured tailoring knowledge available as a result of applying the methodology, an improvement concerning the flow of feedback of tailoring knowledge from project-level to standard process-level seems reasonable: The higher explicitness concerning tailoring activities enables a qualitative and quantitative assessment of tailoring activities and the tailoring effort spent.

B. Discussion of the methodology and outlook

At this point it shall be explicitly mentioned that the presented research is a work in progress, and no ready-to-use methodology or framework has been developed so far in any case. The proposed methodology has so far been discussed with a number of subject matter experts from the domain of EDP management in order to assess its basic understandability, feasibility and the expected benefit. The methodology is not meant to replace existing approaches for mapping, defining and modeling EDPs, but to complement them instead. The proposed methodology is focused on investigating structural process properties and influencing factors that can be qualitatively or quantitatively described or measured. Further intangible aspects, such as company culture, psychological, and sociological effects, are currently beyond the scope of the methodology. At this point, the steps of the presented methodology will form a guideline for further research activities, such as thorough literature reviews. Accordingly, a research agenda for detailing the individual steps has been presented along with the description of the steps in section VI-B. Next, the individual steps will be further detailed as described in this research agenda. Additionally, the overall methodology will be continuously scrutinized, assessed for consistency and applicability, and adapted, if necessary. For example, an adaptation of the methodology to support specific application cases, such as the new development of an EDP (“process synthesis”) or the analysis and rework of an existing EDP is conceivable. Moreover, a number of further case studies as well as use cases for evaluation of the methodology are in preparation with companies, especially, within the size of SMEs. Further extensions of the methodology to address other activities of the process lifecycle are also conceivable, such as addressing aspects regarding the implementation of EDPs within the organizational context.

REFERENCES

[1] *A guide to the project management body of knowledge (PMBOK guide)*. Newtown Square, Pennsylvania: Project Management Institute, Inc, 2013.

[2] A. Albers, N. Burkardt, M. Meboldt, and M. Saak, “Spalten Problem Solving Methodology in the Product Development,” in *Proceedings of the International Conference on Engineering Design 2005 (ICED 2005)*, 2005.

[3] C. R. Amigo, D. R. Iritani, H. Rozenfeld, and A. Ometto, “Product Development Process Modeling: State of the Art and Classification,” pp. 169–179.

[4] C. Argyris, R. Putnam, and D. M. Smith, *Action science,* 1st ed. San Francisco: Jossey-Bass, 1985.

[5] G. C. Baumberger, *Methoden zur kundenspezifischen Produktdefinition bei individualisierten Produkten*. Dissertation, 1st ed. München: Verl. Dr. Hut, 2007.

[6] J. Becker, M. Kugeler, and M. Rosemann, *Process management: A guide for the design of business processes; with 34 tables*. Berlin, Heidelberg [u.a.]: Springer, 2003.

[7] A. Begel and N. Nagappan, “Usage and Perceptions of Agile Software Development in an Industrial Context: An Exploratory Study,” in *First International Symposium on Empirical Software Engineering and Measurement*, pp. 255–264.

[8] L. T. M. Blessing and A. Chakrabarti, *DRM, a Design Research Methodology,* 1st ed. Guildford, Surrey: Springer London, 2009.

[9] T. R. Browning, “The many views of a process: Toward a process architecture framework for product development processes,” (en), *Syst. Engin,* vol. 12, no. 1, pp. 69–90, 2009.

[10] T. R. Browning, “Managing complex project process models with a process architecture framework,” (en), *International Journal of Project Management*, vol. 32, no. 2, pp. 229–241, 2014.

[11] N. Chucholowski and U. Lindemann, “An Initial Metamodel to Evaluate Potentials for Graph-based Analyses of Product Development Projects,” in *Risk and change management in complex systems: Proceedings of the 17th International DSM Conference*, München: Hanser, Carl, 2015, pp. 77–88.

[12] J. Collis and R. Hussey, *Business research: A practical guide for undergraduate and postgraduate students,* 4th ed. Basingstoke: Palgrave Macmillan, 2013.

[13] R. G. Cooper, *Winning at new products: Accelerating the process from idea to launch,* 3rd ed. Cambridge, Mass.: Perseus Pub, 2001.

[14] R. G. Cooper, *Winning at new products: Creating value through innovation,* 4th ed. New York: Basic Books, 2011.

[15] R. G. Cooper and S. J. Edgett, *Lean, rapid, and profitable new product development*. [Ancaster, Ont.]: Product development Institute, 2005.

[16] D. G. Costa, V. C. Macul, J. M. H. Costa, K. Exner, A. Pförtner, R. Stark, and H. Rozenfeld, “Towards the next generation of design process models: A gap analysis of existing models,” in *Proceedings of the 20th International Conference on Engineering Design (ICED15)*, 2015.

[17] C. F. Earl, C. M. Eckert, and J. H. Johnson, “Complexity of Planning in Design,” in *Proceedings of DETC 2001*, 2001.

[18] *Entwicklungsmethodik für mechatronische Systeme*, VDI 2206, 2004.

[19] J. Gausemeier, G. Lanza, and U. Lindemann, *Produkte und Produktionssysteme integrativ konzipieren*. München: Carl Hanser Verlag GmbH & Co. KG, 2012.

[20] K. Gericke and C. Eckert, “The long road to improvement in modelling and managing engineering design processes,” in *Proceedings of the 20th International Conference on Engineering Design (ICED15)*, 2015.

[21] K. Gericke and H. A. Moser, “Adapting a Design Approach: A Case Study in a Small Space Company,” in *Modelling and management of engineering processes*, P. Heisig, Ed.: Engineering Design Centre, University of Cambridge, 2014, pp. 101–114.

[22] M. P. Ginsberg and L. H. Quinn, “Process Tailoring and the Software Capability Maturity Model: Technical Report CMU/SEI-94-TR-024,” Software Engineering INstitute, Carnegie Mellon University, Pittsburgh, Pennsylvania, Nov. 1995.

[23] M. Graner, *Der Einsatz von Methoden in Produktentwicklungsprojekten: Eine empirische Untersuchung der Rahmenbedingungen und Auswirkungen*. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint: Springer Gabler, 2013.

[24] C. Haskins, *Systems engineering handbook: A guide for system life cycle processes and activities,* 3rd ed. San Diego, Calif.: International Council of Systems Engineering, 2011.

[25] M. Indulska, J. Recker, M. Rosemann, and P. Green, “Business Process Modeling: Current Issues and Future Challenges,” in *Advanced Information Systems Engineering: 21st International Conference, CAiSE 2009*, Berlin: Springer, 2009, pp. 501–514.

[26] *Inkrementelle und objektorientierte Vorgehensweisen mit dem V-Modell 97*. München, Wien: Oldenbourg, 1998.

[27] G. Kalus and M. Kuhrmann, “Criteria for Software Process Tailoring: A Systematic Review,” in *Proceedings of the 2013 International Conference on Software and System Process*, New York, NY: ACM, 2013, pp. 171–180.

[28] M. F. Kreimeyer, *A structural measurement system for engineering design processes*. München: Verl. Dr. Hut, 2010.

[29] M. Kuhrmann, “You can't tailor what you haven't modeled,” in *ICPS: ACM international conference proceeding series, 2014 International Conference on Software and Systems Process (ICSSP): Proceedings : May 26-28, 2014, Nanjing, China*, H. Zhang, L. Huang, and I. Richardson, Eds, New York: Association for Computing Machinery, Inc, 2014, pp. 189–190.

[30] S. Langer and U. Lindemann, “Managing Cycles in Development Processes - Analysis and Classification of External Context Factors,” in *Proceedings of the 17th International Conference on Engineering Design (ICED'09)*, Glasgow: Design Society, 2009 ;.

[31] A. Lapouchnian, E. Yu, and A. Sturm, “Re-Designing Process Architectures,” in *2015 IEEE 9th International Conference on Research Challenges in Information Science (RCIS): 13 - 15 May 2015, Athens, Greece*, C. Rolland, Ed, Piscataway, NJ: IEEE, 2015.

[32] U. Lindemann, *Methodische Entwicklung technischer Produkte*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.
[33] U. Lindemann, M. Maurer, and T. Braun, *Structural Complexity Management*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.
[34] S. K. Markham and H. Lee, "Product Development and Management Association's 2012 Comparative Performance Assessment Study," (en), *J Prod Innov Manag*, vol. 30, no. 3, pp. 408–429, 2013.
[35] *Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte*, VDI 2221, 1993.
[36] B. O'Donovan, C. Eckert, J. Clarkson, and T. Browning, "Design planning and modeling," in *Design process improvement: A review of current practice*, J. Clarkson and C. Eckert, Eds, London [U.K.]: Springer, 2005, pp. 60–87.
[37] O. Pedreira, M. Piattini, M. R. Luaces, and N. R. Brisaboa, "A systematic review of software process tailoring," (af), *SIGSOFT Softw. Eng. Notes*, vol. 32, no. 3, p. 1, 2007.
[38] J. Roelofsen, C. Baumberger, and U. Lindemann, "An Approach Towards Situation Specific Planning of Design Processes," in *Proceedings of the 16th International Conference on Engineering Design (ICED'07)*, 2007.
[39] K. Schwaber and M. Beedle, *Agile software development with Scrum*. Upper Saddle River, NJ: Prentice Hall, 2002.
[40] A. Sharafi, T. Wolfenstetter, P. Wolf, and H. Krcmar, "Comparing product development models to identifdy process coverage and current gaps: A literature review," in *Proceedings of the IEEM 2010*, [Piscataway, N.J.]: IEEE, 2010, pp. 1732–1736.
[41] D. Spath, Ed, *Business process management tools 2008: Eine evaluierende Marktstudie zu aktuellen Werkzeugen*. Stuttgart: Fraunhofer-IRB-Verl, 2008.
[42] N. P. Suh, *The principles of design*. New York: Oxford University Press, 1990.
[43] M. V. Tatikonda and M. M. Montoya-Weiss, "Integrating Operations and Marketing Perspectives of Product Innovation: The Influence of Organizational Process Factors and Capabilities on Development Performance," (en), *Management Science*, vol. 47, no. 1, pp. 151–172, 2001.
[44] D. Unger and S. Eppinger, "Improving product development process design: A method for managing information flows, risks, and iterations," (en), *Journal of Engineering Design*, vol. 22, no. 10, pp. 689–699, 2011.
[45] S. Vajna, "Workflow for Design," in *Design process improvement: A review of current practice*, J. Clarkson and C. Eckert, Eds, London [U.K.]: Springer, 2005.
[46] K. Vergidis, A. Tiwari, and B. Majeed, "Business Process Analysis and Optimization: Beyond Reengineering," (en), *IEEE Trans. Syst, Man, Cybern. C*, vol. 38, no. 1, pp. 69–82, 2008.
[47] R. K. Yin, *Case study research: Design and methods*. Los Angeles, London, New Delhi, Singapore, Washington DC: SAGE, 2014.