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SUSTAINABILITY OF MODULAR PRODUCT FAMILIES

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Abstract

A global customer base demanding highly individual products often forces companies to offer a wide range of products. Commonality within modular product families allows great product variety through lower internal variety of components and processes. Companies then struggle with sustainability of modular product families, that is, managing commonality across the product family lifecycle when modular product families are changed to react to new customer demands.

Based on a literature review, the current support from academia for handling the sustainability of modular product families is presented. The findings are consolidated into a conceptual schema. The subsequent successful use of the conceptual schema in the process planning of a medium-sized enterprise, developing and producing elevators, identified further factors that influence the sustainability of modular product families. These factors will be addressed in the future, with support from academia.

Keywords: Product families, Product structuring, Design management, Engineering change

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1 INTRODUCTION

A global customer base often demands highly individual products. Large companies and small to medium enterprises (SMEs) have to handle the increase in external product variety that results from customizations. Two types of product variety exist (Martin and Ishii, 2002): spatial variety describes variety in the current product program; and generational variety refers to variety in the course of time (Figure 1a). An increase in both types of external variety creates an increase in internal product and process variety, which results in high complexity costs. Simultaneously, global competition results in high cost pressure. Proven solutions to the challenge of offering variant products at low cost are based on commonality in modular product families (mPF). Commonality can reduce internal variety of components and processes and is either spatial or generational.

1.1 Challenge of sustaining a modular product family

Since 2012 the Institute of Product Development and Mechanical Engineering Design (PKT) at the Hamburg University of Technology (TUHH) has hosted five training workshops on different modularization methods (Krause et al., 2013), one of which is the Integrated PKT-Approach for Developing Modular Product Families (PKT-Approach) (Krause et al., 2014) (Figure 1b), which combines a technical-functional modularisation with module drivers. Course participants were designers and managers from the design departments of companies in aviation, transportation, materials handling, shipbuilding, machinery, personal safety, bearings, plant engineering, test plants, and production systems sectors, as well as consultancies. At each workshop, participants were asked to report challenges that have arisen for them in practice using mPFs. The evaluation of responses from 45 participants identified sustaining mPFs for a long time after definition as one of the seven main challenges (Beckmann et al., 2014). A follow-up, semi-structured interview study of 11 workshop participants (who had recently attended a workshop in 2013) confirmed this. The interviews and workshop responses motivated the research presented in this paper.

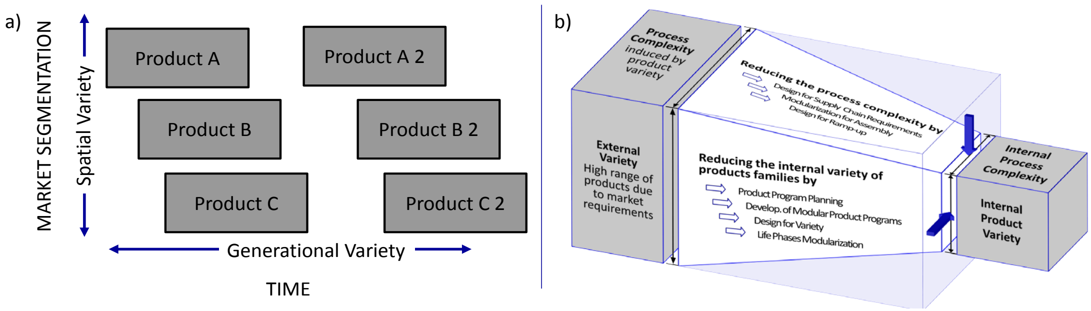

Figure 1. a) Varity types (Martin and Ishii, 2002) b) PKT-Approach (Krause et al., 2014)

For this paper, sustaining an mPF is defined as managing commonality during the product family lifecycle when the mPF is changed after the product structure concept has been defined. The main forces for change are new customer needs and technological evolution, which result in deterioration of the current state of the mPF. Small, sustainability upgrades are one way to counter deterioration and elongate the mPF lifecycle (Engel and Browning, 2008). Further forces for change exist and can either be initiated from outside of the mPF (e.g. changing laws) or emerge from the mPF (e.g. errors) (Eckert et al., 2004). The change can also spread from the initially affected component to other parts of the product variant and in mPFs spread to other product variants due to commonality (Jarratt et al., 2011). A certain degree of function binding, interface standardization and loose coupling is required to archive modularity (Salvador, 2007). These properties also make modular products better than integral products in changing environments and at meeting evolving needs throughout the entire lifecycle (Fricke and Schulz, 2005). To describe change in general, three aspects are needed (Ross et al., 2008): the change agent, mechanism, and effect. The change agent is the force required for the change to occur, e.g. new customer needs. Change mechanisms are the paths that the system can take to transition from one state to another. The change effect is the difference in states before and after the change has occurred. Each change agent can affect the state of spatial commonality.

1.2 Aim of study and paper structure

The objective of this paper is to identify factors that influence the sustainability of mPFs, which can then be supported in the future. With this planned support, the sustainability system and its implementation can be efficient and effective. Sustainability of mPFs can be supported during the architecture development phase (1). Furthermore, companies can be supported during evaluation and implementation of changes within the lifecycle after the mPF concept has been defined, i.e. the sustainability phase (2). This paper is structured into two parts, A and B. Part A contains answers for both phases (1 & 2) of the research questions (RQ):

- RQ1: How is academia currently supporting the sustainability of mPFs and what are the identified influencing factors?

The findings of Part A for the sustainability phase (2) are consolidated into a conceptual schema. Based on the transfer of the schema to the process development of an SME, part B shows answers for:

- RQ2: What further influencing factors and challenges can be observed during the transfer of the literature findings into the process planning of an SME?

2 RESEARCH APPROACH

The following sections describe the research approaches for Parts A and B.

2.1 Part A - Literature review and consolidation of a conceptual schema

An mPF literature review is used to identify research to-date, and analyse whether the literature focuses on spatial or generational variety and at which stage of the mPF lifecycle support exists. The literature includes a selection of significant methods that were characterised in 2013 by Krause and Ripperda (2013). Besides methods, background literature and literature on variety and engineering change is analysed for statements connected to the sustainability of mPFs. At the end of Part A, the strategies which address the sustainability phase of mPFs are gathered and consolidated into a conceptual schema of mPF sustainability processes.

2.2 Part B - Application of the conceptual schema at LUTZ Elevators

In the article "Transferring Design Methods into Practice", Wallace (2011) observes that in many cases there is nobody in academia or practice responsible for transferring design research knowledge to companies. The conceptual schema from Part A is based on "Design research knowledge". To support industry with "Design research knowledge", "Knowledge transfer" is necessary (Figure 2).

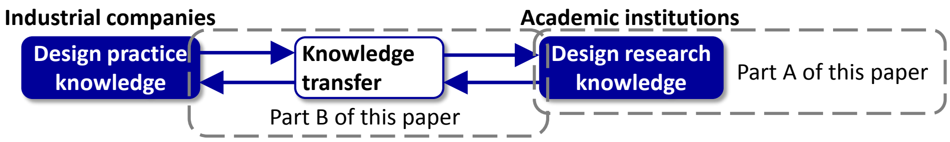

Figure 2. Knowledge transfer – based on Wallace (2011)

In Part B, the transfer from academia to industry is carried out and observed by academia to create additional "Design research knowledge". This is used to help identify further influencing factors that can be addressed using future support developed by academia. Addressing RQ2 requires an SME that uses mPFs. The mPF should cover a large spatial variety and the context of the mPF should generate change agents that result in generational variety. In a joint research project with PKT, the medium-sized enterprise LUTZ Elevators is pre-developing an mPF concept. The company is currently at the stage of defining processes for the new mPF. It is investigating whether the conceptual schema can be used in practice to support the planning of an mPF sustainability process.

The knowledge transfer is supported by detailed analysis of company methodical needs and structure, and a visual description (Beckmann and Krause, 2013) of existing processes and the methods to be introduced. The empirical data were gathered using participant observation during process planning. To identify where further detailing and additional support is required, notes and documents from the process planning process were analysed.

3 PART A - BACKGROUND

Section 3.1 presents the results of the literature review, which are then consolidated into a conceptual schema in Section 3.2. Both are discussed in Section 3.3.

3.1 Results Part A - Literature review findings

The research community currently supports the sustainability of mPF with ways to plan and structure mPFs that are robust and flexible. In the characterization of product structuring methods by Krause and Ripperda (2013), about half of the methods consider spatial product variety only partially or not at all. Recent publications voice doubt about the possibility of applying methods that do not model spatial variety to mPFs because the dependencies, due to spatial commonality, can be too numerous to focus on only one of the products and assign methodologies to it (Kissel, 2013). The reasons for grouping components to modules can be either technical-functional relations or strategic aspects.

Technical-functional structuring methods use function structures and component interactions as the basis for modular concepts. Sudjianto and Otto (2001) developed a concept to model function structures that shows spatial commonality within an mPF. Ever since Pimmler and Eppinger (1994) proposed the use of a Design Structure Matrix (DSM) to identify modules, it has been widely used to analyse interactions among functions and components. Harlou (2006) states that the DSM does not propose a way to handle variety; he emphasizes the importance of the DSM in understanding the significance of interfaces and interactions among components. Stone (1998) uses heuristics to identify modules based on the function structure, without highlighting spatial commonality or variety. In a complementary method, he proposes a Device Similarity Matrix to compute the potential for shared modules (spatial commonality) between product variants. Martin and Ishii (2002) focus on generational variety, though their concepts can also be applied to spatial variety. They analyse coupling among product components and compute a generational variety index to design long-term stable platform concepts.

Strategic Module Drivers can be used to pre-emptively consider future changes during the mPF lifecycle, decouple components and increase changeability. Erixon (1998) specifically mentions the drivers "Carry-over", "Technological evolution/technology push" and "Planned design changes/product planning", which relate to generational variety. Expanding Erixon's module driver concept, Greisel et al. (2013) define Adaptability Drivers and mention change scenarios as drivers.

The planning framework of Robertson and Ulrich (1998) includes a product plan that shows which product variants will be delivered at which time, as well as a differentiation plan showing variety and a commonality plan showing commonality during the mPF lifecycle. Harlou (2006) introduces an mPF model called the product family master plan. He differentiates between design units, re-used design entities, and standard designs (those that are not re-used). Addressing generation variety, he also mentions future design units and future standard designs, while highlighting a need for investigation of how to model the timing aspects of standard designs and architectures, and control it. Two other recent approaches for development of mPFs rely on forecasting and scenarios because the design of product architectures in general, and modular platforms in particular, is based on static requirements (Schuh et al., 2012), (Bauer et al., 2013). Schuh et al. (2012) create module roadmaps and Bauer et al. (2013) use a Multiple Domain Matrix (MDM) to identify components as candidates for platforms or modules. Recent analyses of the literature results in the conclusion that approaches to manage spatial variety generally focus on static rather than dynamic variety (Abdelkafi et al., 2011). Boas et al. (2013) criticize the existing literature, as it assumes that all variants of an mPF are developed, manufactured and operated simultaneously.

The reviewed body of literature on mPFs sparsely addresses the sustainability phase. Not focusing on mPF but the product programs in general, Schuh (2005) warns that over time product programs will be inflated to an unmanageable state if companies do not have controlling instruments. To prevent this, he proposes periodic or situational order-related approval procedures. Ehrlenspiel et al. (2007) mention disordered, chaotic change processes as a reason for variety.

There are three options to respond to a change agent (Dellanoi, 2006):

1. Modification or extension of the product family, increasing the cost of each variant due to additional development efforts. The subsequent expansion of an existing product family leads to additional costs that may have an impact on all other variants.
2. Development of a new variant independent of the product family (special builds).

3. Non-fulfilment of the customer request.

A study of Boas et al. (2013) shows that the companies that are addressing the commonality aspect with specific change boards and processes are more successful in achieving their commonality goals. Methodical approaches to support companies during the planning and implementation of such change processes for mPFs were not found. Generic change processes and corresponding success factors can be found in literature on engineering change, e.g. Lindemann and Reichwald (1998). Engineering change literature does not focus on mPFs but mentions that robust and flexible architecture is required to handle generational variety. Jarratt et al. (2011) mention that change in mPFs, with spatial commonality, is difficult to manage because the change of a shared component can affect all product variants that contain the shared component.

3.2 Results Part A - Conceptual schema for sustainability processes

This section presents a conceptual schema for mPF sustainability processes that consolidates findings from Section 3.1. The literature shows that the sustainability of mPF requires a change (Boas et al., 2013) or approval (Schuh, 2005) process to systematically evaluate changes to commonality. For each change agent, a decision base, consisting of the choices, information and preferences (Howard, 1988), has to be refined and evaluated. Choice means alternative solutions. Information is the models, relationships and probabilities that can be important when characterizing different change mechanisms and their change effects. Preference is the value of an alternative, in terms of time and risk preference.

Literature on engineering change served as a basis for the steps in the conceptual schema. Jarratt et al. (2011) describe a model of a generic change process and provide the outline of the steps shown in Figure 3. The schema starts with the current state of the mPF and the collection of change agents. As mentioned by Schuh (2005), the change agents can be reviewed either when driven by a situational event or periodically. The schema focuses on the assessment step of the change process. The sub-steps of "Risk/impact assessment of solution(s)" are detailed, based on the work on change propagation by Eckert et al. (2004) and Reichwald et al. (1998), who stress the importance of estimating the impact on organizational units and processes. During all steps, stakeholders are identified and integrated into the process. After the assessment step, a change board selects a solution alternative. The specific solution corresponds to one of the three types defined by Dellanoi (2006). An earlier version of the schema, with a more detailed description of the assessment steps, can be found in Bahns and Krause (2013).

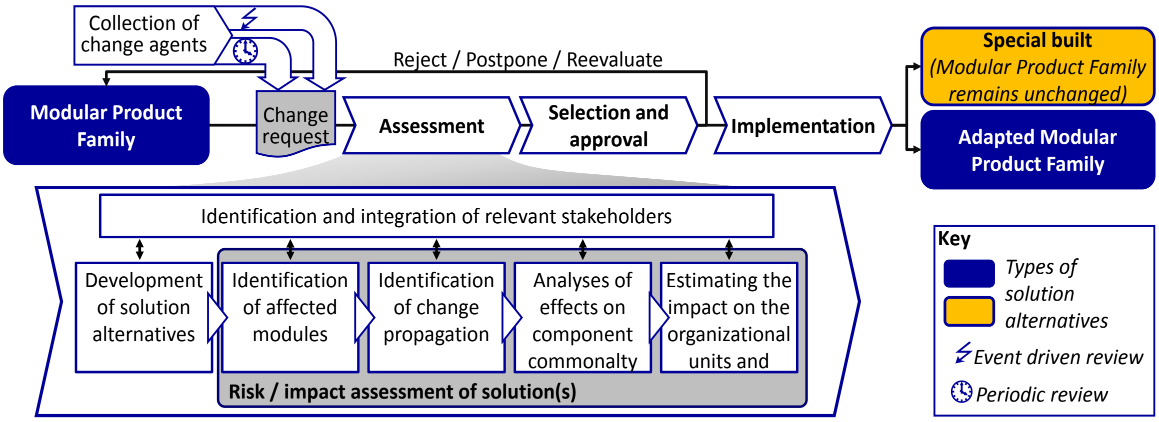

Figure 3. Conceptual schema of modular product family sustainability processes

3.3 Discussion Part A - Current support for modular product family sustainability

The current support from academia for the sustainability of mPFs can be characterised as follows:

- A focus on architecture development in the early phases
- Only initial support provided for the sustainability phase, without adequate methods.

Based on the literature review, the mPF sustainability requires:

- Robust and flexible mPF concepts
- Change processes and controlling instruments that make decisions from an mPF perspective.

The results in Section 3.1 show that some methods rely on forecasting to anticipate future changes during product structuring. Forecasting changes should be part of every mPF project because it allows the decoupling of the specific parts of the architecture. However, forecasting all future changes is almost impossible in longer product lifecycles. Pahl et al. (2007) say that requirements change and solutions can only be optimised for a particular set of circumstances. Both the architecture development phase and the sustainability phase are important. Support for the architecture development phase lays the foundation for efficient and effective maintenance in the later sustainability phase.

Literature on mPFs focuses on program planning and the architecture development phases rather than subsequent phases of development and changes during the lifecycle. Pirmoradi et al. (2014) found this in their review as well. They perceive mPF commonality targets and enforcing those targets during the product family development process, as well as considering dynamic issues as an important future research direction.

For mPFs, there is a lack of systematic techniques to design a sustainability system with specific processes. Nevertheless, the results in Section 3.1, combined with design knowledge from the engineering change domain, allowed the generation of a conceptual schema for mPF sustainability processes.

Future research should investigate whether methods for architecture development, mentioned in Section 3.1, also support the investigation of change mechanisms and effects in the sustainability phase.

4 PART B - TRANSFER OF THE CONCEPTUAL SCHEMA TO INDUSTRY

Section 4.1 shows the results of the transfer of the conceptual schema, described in Section 3.2, to process planning in industry. The results are discussed in Section 4.2.

4.1 Results Part B - Sustainability process planning in industry

LUTZ Elevators is a medium-sized, family-owned and run enterprise that develops and produces high-end elevators for application in buildings and marine environments. The company is pre-developing an mPF concept ("Modulbaukasten") using the PKT-Approach; employees, particularly those in the design department, are taught fundamental knowledge and methods for mPFs (Krause and Gebhardt, 2014). The new company strategy is no longer to engineer to order each elevator variant, but increasingly to configure them from the pre-developed mPF. LUTZ Elevators has to establish a new order fulfilment process and a supporting sustainability process (Figure 4). The conceptual schema (Section 3.2) and methodical supports developed by PKT have been transferred and adapted to the company. The new processes in the elevator company distinguish clearly between a time critical failure management process, which is part of the order fulfilment process, and the sustainability process of the mPF.

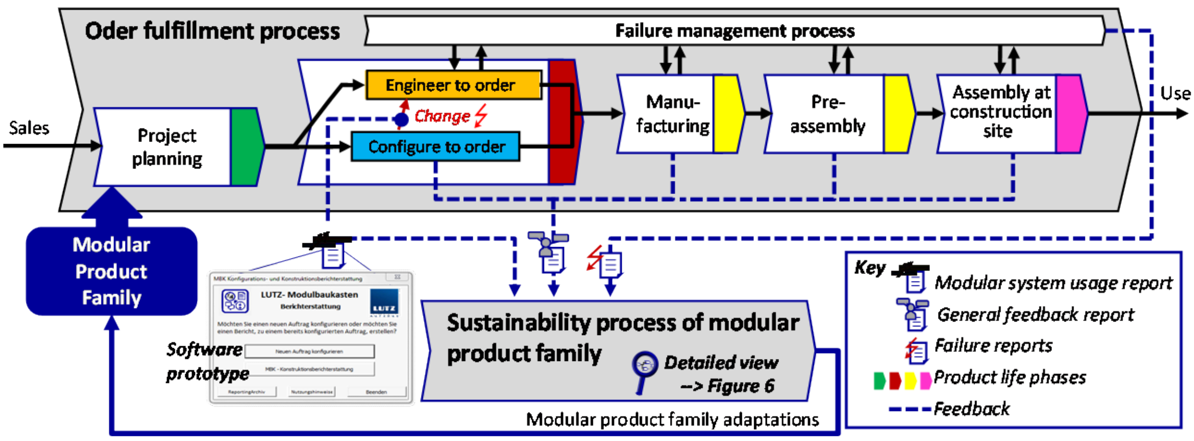

Figure 4. Order fulfilment process supported by sustainability process

In the new order fulfilment process, the designated order-processing path of each module is defined by sales and the project planning department for each elevator order. Each module of an order can be processed on the "Engineer to order" path or the "Configure to order" path, which uses the pre-developed modules of the mPF. Both paths will be part of the future strategy, since they are based on different business cases.

For the Configure to Order path, a new module configuration reporting process is introduced to overcome the old habit of designing each part individually. If the customer requirements cannot be met with the existing modules of the mPF the Configure to Order path chosen by sales is abandoned. The designer is liable for creating a "Modular system usage report", arguing the need for change, an mPF change agent. This should hinder uncontrolled creation of new unwanted designs within the mPF and support mPF sustainability. Within the order fulfilment process, a failure management process addresses failures recognized between "Project planning and configure to order" and "Assembly at construction site". Immediate solutions for the specific product variant are developed. The selected solution in the failure management process, e.g. creation of new module variants, is not allowed to cause changes in the mPF. It is initially automatically classified as special build (Figure 3) because the impact of the change on the whole mPF cannot be analysed when under time pressure. Only a "Failure report" containing a failure and solution description is collected and serves as an mPF change agent. As part of each order, a "General feedback report" is created. This allows employees from all product life phases to state improvement ideas for the mPF. For the reporting process, a software prototype was developed. This software prototype utilizes a visual product representation called a Module Interface Graph (MIG). It visualizes interfaces and commonality in the mPF (Gebhardt et al., 2014). The MIG is used in the PKT-Approach and was thus used during the development of the mPF concept (Figure 5).

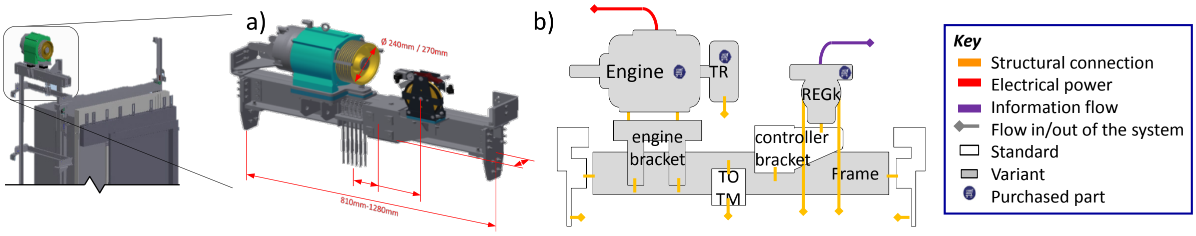

Figure 5. Elevator engine room: a) CAD Model; b) MIG (Krause and Gebhardt, 2014)

The sustainability process (Figure 6) starts with preliminary collection, analysis and filtering of the given reporting documents from the order fulfilment process. During process planning with LUTZ Elevators, the need to distinguish between issues related and not related to the mPF became clear. Only issues relevant to the mPF are included in the sustainability process. These change agents, e.g. ideas and problems, are sorted according to their urgency, estimated implementation efforts and change effects. To fulfil the task, a new "Modular System Officer" is needed. The Modular System Officer must be highly familiar with the mPF and sensitive to possible effects of the variety and commonality changes in both the product and process domains. The sustainability process contains three further main elements. The consideration of external market trends is used in combination with the reporting documents from the order fulfilment process to identify change agents. During the transfer of the conceptual schema to LUTZ Elevators, two magnitudes of the sustainability process described in the conceptual schema are necessary: a heavyweight sustainability process and a lightweight sustainability process. In the heavyweight and lightweight sustainability processes, the decision base will be refined, following the assessment steps of the conceptual schema in Figure 3.

To establish far-reaching changes in the mPF, the heavyweight sustainability process is used. This process is used to deal with change agents that may have a larger change effect on the mPF and connected processes and/or require more workforces for the change mechanisms. The change agents are stored until the heavyweight process is trigged periodically by the Modular System Officer and a cross-department meeting is called. The team of managers from the different departments evaluates the potential change mechanism and potential effects. Decisions are made and the Modular System Officer is provided with the required additional resources to further refine the decision base or to carry out a selected change mechanism in the implementation step. Beside internal technical feedback from the order fulfilment process, the heavyweight sustainability process receives input from external market considerations on a yearly basis. Company management and representatives from the sales department are invited to a workshop moderated by the Modular Systems Officer to review the success of products sold, evaluate new market trends and refine external product variety offered in the future.

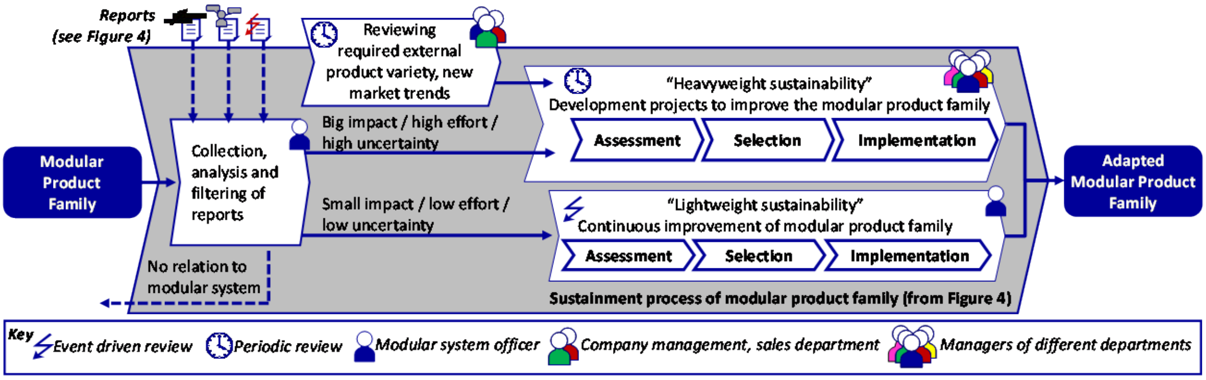

Figure 6. Detailed sustainability process

The lightweight sustainability process is a continuous improvement process that gives the company the opportunity to improve the mPF in parallel with day-to-day business, such as implementing minor changes with low uncertainty, small estimated risk for negative effects and low estimated effort to implement. The Modular System Officer is in charge of the overall process and uses a percentage of his working hours to continuously improve the mPF, through improvement of CAD templates or removing errors in the mPF.

Currently, LUTZ Elevators is still in the process of developing the mPF. The sustainability process was included in the new process plans of the company together with the new order fulfilment process, after discussion with company management. The processes and the software prototype were valued and will soon be tested and introduced.

4.2 Discussion Part B - Influencing factors and challenges

The transfer of the conceptual schema from Part A to the planning of a process to sustain the mPF within an SME provided valuable results. Even though the schema is based on literature that does not particularly focus on SMEs, the results in Section 4.1 show that the findings can be applied to an SME. The participants of the process planning are convinced that the use of the conceptual schema made the order fulfilment and sustainability process planning more efficient.

During the knowledge transfer, the following further influencing factors and challenges were observed:

- The influence of time preference and its interdependencies with risk preference in mPF sustainability decisions.
- Existence of stakeholders with an mPF perspective to select adequate refinement processes of the decisions base during the sustainability process.
- Availability and carry-over of mPF information from architecture development into the sustainability phase.

A finding during knowledge transfer was that urgent changes could cause sustainability implantations with long-term negative effects. The challenge is a time preference issue. Solutions can have a fast and inexpensive change mechanism for a particular product variant of the mPF but have long-term negative change effects on commonality for the entire mPF. A high preference for a short-term outcome can result in insufficient assessment and uncertainty around the long-term effects on commonality in the mPF. During the selection and approval of solution alternatives, the risk of the alternatives can be misjudged due to this uncertainty. A solution identified for LUTZ Elevators to handle the trade-off between risk and time preference is decoupling the urgent changes from the sustainability of the mPF. In this case, it was possible to decouple change agents from failure or new customer wishes with special builds. This might not be possible in other industries, especially if the company does not have a parallel engineer to order or make special builds.

In the SME example, the sustainability processes are managed by a new position, the Modular System Officer. The task of the Modular System Officer is to steer a systematic procedure, to transform opaque variety and commonality decision problems into transparent decisions, using a sequence of defined steps. Commonality is an emergent property of the system because it can only be determined in the context of the whole mPF. Therefore, the role of the Modular System Officer is to look at the mPF from the system perspective. Similarities between this role and the role of a systems architect, as described by Haberfellner (2012), exist. Changes to the modular structure and commonality can be advantageous or disadvantageous; the Modular System Officer has to ensure that decision makers can make their decisions consciously. To ensure an adequate decision process, the officer has to observe the unfolding circumstances within the mPF and select an adequate process, considering the accuracy-effort trade-off to refine the decision base during the sustainability process.

A further key aspect is support, with models that contain specific mPF information, as well as heuristics and metrics to evaluate the sustainability phase. During process planning at the elevator company, models from the mPF concept development phase were proposed as candidates to support the recurring sustainability process. Models, heuristics and metrics can be used to determine suitable change processes and to refine the decision base during the change processes. Future research will investigate how models that are used during the initial development of mPFs can also be used during the sustainability phase, e.g. the support mentioned in Section 3.1. In contrast to the initial development of the mPF, during sustainability the developer can rely on existing models. For the models to stay valid, they have to be updated due to changing conditions.

5 GENERAL VALIDITY, CONCLUSION AND OUTLOOK

The findings from the use of the conceptual schema in an SME should be interpreted with care. The study shows identified needs of an SME, who relied in the past on an engineer to order processes and who is currently implementing an mPF. There is a level of uncertainty about how relevant the identified factors are to the needs of other companies. Further research needs to show whether the identified factors are also applicable in large companies, in which other factors might dominate, e.g. PLM integration. Since circumstances did not allow the use of control groups, the efficiency gain during process planning cannot be quantified. Full evaluation of the efficiency and effectiveness of the planned processes will be possible when the mPF is used and a representative number of changes have been handled. The goal of this paper is not to present an ideal prescriptive process, but to share important observations made and factors identified during process planning. In applicability, the conceptual schema served as an important basis for the planned processes. The use of the conceptual schema by an SME shows that both periodic and event-driven sustainability processes are required at different magnitudes. The next step is to evaluate the implementation and use of the planned sustainability process at the SME, LUTZ Elevators. Based on the outcome, the conceptual schema will be further developed and tested in other companies. Support for the sustainability phase, based on the identified factors, is being developed in parallel.

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