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KNOWLEDGE-BASED DEVELOPMENT: INTRODUCING PORTFOLIO MAPS AND PRODUCT ARCHITECTURE AS BASIS FOR IMPLEMENTATION

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ABSTRACT

Many companies experience that they use too many new-product development resources in (re-) developing products that are derivatives of previous ones. Product designs are sometimes uncritically copied into new projects and adjusted to match new requirements and needs. Since the products are not developed for reuse and improvement, unexpected modifications drive up the work load, leading to increased cost and lead time, and lower quality.

The standardization approach introduced in this paper uses the product architecture as a backbone for knowledge-based development, assuming that value is created within both the traditional product(ion) value stream and the knowledge value stream. Before applying this approach, however, it is necessary to (a) organize the product portfolio, (b) sharpen the product strategy and (c) establish a common product architecture. In this paper, the products of a case company have been analyzed, structured and modeled. The result is a product portfolio map, including variants on functional, physical and architectural levels - within and across modules. It provides a visual product model on system and module levels, including current and near-future variants.

Keywords: product structuring, product modelling, visualization, product portfolio, knowledge-based development

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1 INTRODUCTION

Nowadays, the ultra-competitive pressure in the marketplace is forcing companies to deliver products with improved performance and quality while reducing cost, development and lead time. One countermeasure is establishing a standardization strategy that leverages reuse and continuous improvement in combination with a culture of sharing, transferring and storing deep product knowledge. The key to remain competitive in today's hostile business environment—no matter whether the company is in the high or lowvolume market segment—is to develop capabilities for successfully integrating standardization and customization into one unified product portfolio strategy (Patterson 2005, Larsson 2007). However, such an approach has to be balanced with efficient processes for development of valid products that provide high value to customers whose needs are diversified, sometimes conflicting and even opposite.

Regarding reuse of design options and knowledge, many industrial companies commonly discover that they use resources in reinventing products that are virtually copies or derivatives of previous ones. Sometimes products are reused uncritically by copying former solutions into new projects. As a consequence, many modifications and changes are necessary to adapt the former solution to the requirements associated with the new environment, which will increase the work load, especially when changes are realized late in the process. The root cause is that the original solution was designed to solve a specific task or job within a specific product (or project) system—and not for reuse, maintenance, upgrading or application within a generic product architecture.

One approach to leverage standardization in new product development (NPD) is establishing a commonization strategy for individual parts and assemblies that are to be used in different product configurations (standard modules); i.e., ones that are agile in regard to changing requirements, technological progress and specific customer needs (Mortensen, Hansen, and Hvam 2011). However, this implies front-loading the NPD process because influential factors such as product design elements, potential future adaptations and internal as well as external drivers have to be analyzed carefully in order to create a well-structured product strategy based on a product architecture (Ulrich 1995).

For many mature companies, their business strategy includes offering incremental product innovation with basis in an existing product portfolio without a common product architecture. In order to establish a robust architecture founded on standards, products need to be restructured at different levels of abstractness. This requires a thorough analysis of the company's products, along with an approach for (re)arranging parts and modules, both on abstract and concrete product model levels, including requirements, functions, principal solutions, physical modules/parts, and their interfaces (Ulrich 1995). The product architecture needs to be flexible to accommodate a wide range of product variants, providing a platform for technical improvements of future applications (Harlou 2006). Secondly, standardization must enable scalability to provide applicability to a large number of components, hence reducing time, workload, and cost. Visualization of building blocks and dependencies helps create an overview of such a complex system (Hansen, Mortensen, and Hvam 2012), and can also serve as a tool for implementing the product architecture into, say, PLM software systems (Harlou 2006).

It is believed that a thorough description of a systematic approach to establish product architectures can serve as a contribution to application of standardization, reuse and continuous improvement within lean product development (LPD), turning it into a robust base for knowledge-based development (KBD). Standardization, knowledge management processes, customer value, and continuous improvement are all part of LPD (Morgan and Liker 2006). Although the execution of LPD is complex— whose success implementation would represent a competitive frontier—its basic principle is relatively simple; i.e., to provide high value to the customers while eliminating waste and minimizing enabling work that does not directly create value. Although many generic LPD frameworks and components are commonly reported in the literature, implementation best-practices are rarely described to a detail level where procedures and practices foster transparency for application in different companies, industries and cultures (Welo 2011).

This paper proposes a strategy to map existing product portfolios, sharpening the product strategy and using it as a starting point for implementing a KBD framework. Unlike the relatively straightforward approach of establishing product architectures from scratch, it is much more challenging to establish an architecture that fits within an existing product portfolio, whose composition stems from more or less coordinated projects. These structures enable the analysis of a product portfolio, establishment of a commonization strategy and the creation of a common product architecture. Portfolio maps, including short and long-term options have been established by carefully studying select products of a case company. The focus has been placed on designing visual structures as enablers for standardization

within a KBD framework that supports continuous improvement, reuse and effectiveness.
This leads to the following research questions:

How can knowledge from development efforts in customer-specific products be converted into a knowledge framework which enables product teams to efficiently develop valid future products?

How can an existing product portfolio along with the variance of product and prospective options be mapped to provide the base for implementing a common architecture?

2 PRODUCT ARCHITECTURE AS AN ENABLER FOR MORE EFFICIENT NPD EXECUTION

In this paper, multiple projects of a Norwegian case company have been analyzed. Since the company operates globally, different governmental requirements and legalizations (e.g. changing environmental prescriptions) need to be considered along with changing requirements between different customers. Hence, a myriad of adaptions need to be done between the projects, even though the basic products have just slightly different functionality. This makes the product portfolio escalate to a (unnecessary) high number of variances. In contrast to today’s ad-hoc situation, where each customer (project) indirectly controls its NPD focus, the case company wants to establish a future NPD system that makes it possible to proactively propose predetermined design solutions to customers. However, this can only be materialized together with a clear product strategy and product design portfolio that offers necessary possibilities for variant handling.

Like many other companies, the case company has potential to improve their ability in reusing product concepts and related knowledge, as well as defining a commonization strategy. The current design, engineering and development practices can be described as a ‘copy-and-paste’ approach, as illustrated in Figure 1 (left side). Useful and promising solutions for finished projects are copied into the new project and subsequently reconfigured and reengineered to comply with new requirements, customer wishes, and technology state-of-the-art. In many cases, however, the re-work turns out to be more labor-intensive than initially expected, resulting in delayed product deliveries, skyrocketing costs, and using engineering resources for firefighting problems rather than innovating new products. This experience is in accordance with observations described in literature about LPD. According to Kennedy (2010), the problem is due to early settings of schedules, detailed requirements and the system concept, leading to late emersion of critical knowledge gaps followed by design loopbacks. The outcome is typically project delays, costs overruns and repetition of the problems in the next projects.

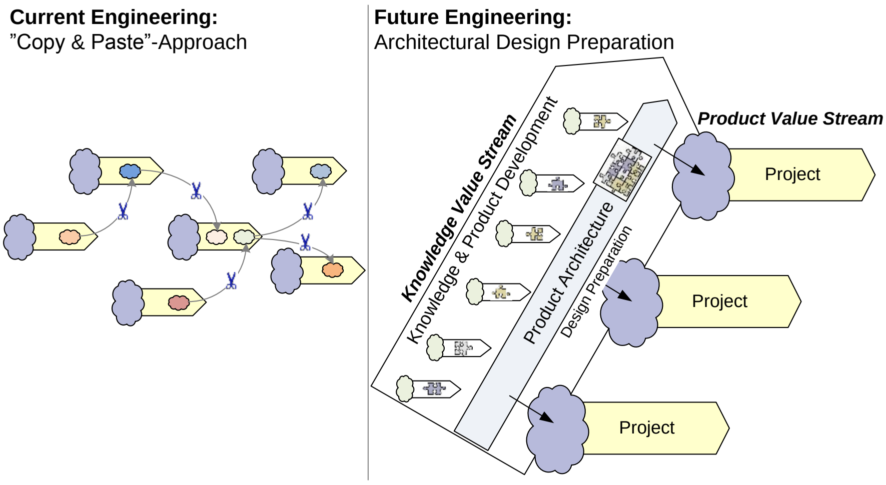

Figure 1. Current reuse of product knowledge and desired future approach

Since such an approach generates considerable waste (Mascitelli 2007), the case company wishes to restructure the product portfolio and introduce a knowledge-based approach, which is illustrated on the right hand side in Figure 1. Instead of developing a product for a certain delivery (Engineer-to-order (ETO)) (Hansen et al. 2012b), generic designs are developed and prepared independently from projects (knowledge value stream). The solution space is moved from an ETO to a configure-to-order (CTO) approach, where projects are executed within the product value stream. A well-established product architecture may be the base for structuring the development and for managing product variants out of a set of pre-developed elements. The design strategy includes developing solutions to provide a well-defined product portfolio with clear variants for the present and the future. In this way, the case company aims to make the NPD process more predictable and effective, and less dependent of certain projects. A challenge with this approach is to guide customers in the direction of standardized solutions in order to reduce internal complexity (Hansen et al. 2012b). Product components are developed in order to satisfy a certain performance range (target) rather than satisfying a specific set of firm requirements. The idea of developing a performance range is schematically illustrated in Figure 2, which shows performance mapping of a set of deliveries with a specific performance on the left and the associated performance range that was covered by different deliveries on the right. The performance characteristics are global, which means that they represent performance properties of the system as a whole.

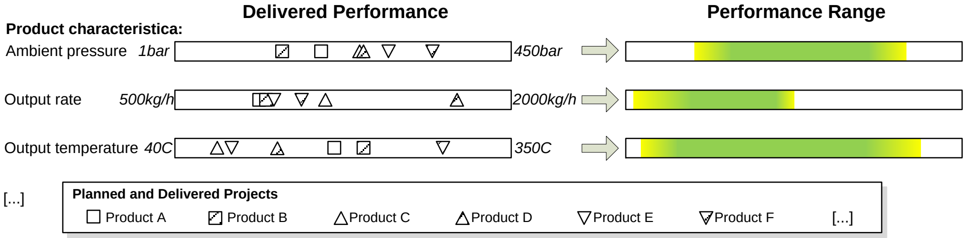

Figure 2. Performance Mapping

It is also believed that a CTO approach with separate research and development as a part of the knowledge value stream may enhance cross-functional cooperation and communication between engineering, marketing, manufacturing, customer, etc., creating a more holistic understanding of the product and its alignment with company strategy. However, it is challenging to establish the desired framework because the way of structuring products and procedures needs to be changed, and the company's value stream aligned (Riitahuhta et al. 2011). Research could be performed independently of specific customer wishes by the aim to innovate and create future value through achieving improved performance characteristics and hence pushing the knowledge value stream forward. Project development teams could then independently pick up generic solutions that were discovered in the research department and configure these into customer specific solutions. Another organizational possibility could be to merge and integrate long-term research and project-specific development to avoid the danger of losing track with the customer in research. Both approaches have their pros and cons, which will not be discussed further in this paper.

3 STATE-OF-THE-ART IN EXISTING METHODS IN PRODUCT ARCHITECTURE MODELLING AND MAPPING

The implementation of the KBD approach described in the former section requires mapping of the product portfolio to get an overview of the product portfolio and strategy, including current and future variants, which will be the subject in the rest of this paper. As a next step, the product portfolio, mapped in portfolio maps, needs to be restructured into a robust product architecture. To summarize aspects of a product architecture according to basic definitions, strategic product focus and visual mapping possibilities, a brief literature review will be made as an introduction to this section.

3.1 The Role of the Product Architecture in Engineering Design

Some of the basic steps in engineering design (e.g. Pahl et al. (2007), Hubka, Andreasen, and Eder (1988), VDI2221 (1993)) are to create functional and physical building blocks, which define the base for developing a product architecture. Ulrich (1995) describes the product architecture as the arrangement of functional elements, combined with the mapping of functional to physical components, and the specification of the interfaces between the physical components. In other words, the product architecture includes three important elements: functional building blocks, physical building blocks, and their interfaces. One basic goal of the product architecture is to support modularity, and hence the possibility of creating several variants out of the same basis product (Pahl et al. 2007).

In order to establish a modular product architecture, it is essential that interfaces are specified and standardized so that modules can be changed and upgraded, while the architecture remains the same. Hence, it is important to forecast several future scenarios (options and developments) because the product architecture should usually remain stable over several product generations, as modules are changing and adapted to technical progress (Harlou 2006). A design unit becomes a standard design once it has been decided that it will be used in more than one product (Harlou 2006). It represents a known entity within the enterprise and will therefore reduce risk, which is the essential purpose of any value creating effort in NPD.

3.2 Strategic Importance of the Product Architecture

Architectural decisions should be made during the early phases of the development and systems engineering (SE) process (Haskins 2011), where research and design issues play a lead role (Ulrich 1995). About 75% of the product's manufacturing costs are dependent on the product design (Ehrlenspiel 1985), which underlines the importance of right design decisions in early development phases. Front loading of the NPD process is also a main issue of LPD, trying to detect problems early to avoid critical situations (Morgan and Liker 2006).

In addition to structuring the product, the product architecture can be a strategic tool for managing product families and variants (Sanchez, Commerce, and Research 1994), and as a knowledge management tool. This can be used as a key role to discover bottlenecks and discover possibilities for strategic learning and capability development. When an architecture provides the right degree of flexibility, it can be used for strategic initiatives such as exploring customer needs for various potential configurations, maintaining the market leadership by providing possibilities for product extensions or upgrades, and reduced cost due to a high amount of standardized components (Sanchez and Collins 2002). Most firms do not have a systematic framework for capturing, sharing, finding and reusing knowledge that is available (Sanchez and Collins 2002). This results in both a lack of effectiveness, since problems might be solved repetitively, and increases insecurity if the company is capable of having enough expertise to commit to certain projects. A well-defined product portfolio can easily be used for comparing capabilities against needs, where components that require redesign or NPD can be identified.

3.3 Product Architeture Modeling

According to Bruun and Mortensen (2012) two major ways of modelling a product architecture do exist. One is *computer-modelling*, applying, for instance, a PLM-system intending to build software computer models. In addition, there is *phenomenon-modelling* which illustrates the product architecture visual in a format that enables its information to be transfered to a computer model. It provides details and maintains the overview in order to aid engineers in decision-making. The approach of portfolio maps to be introduced later in this paper is a phenomenon approach, too. Accordingly, some common visual ways to model a product will be introduced herein.

The *functional structure* characterizes the functional model of a product describing flows of material, data, and energy. It models the product independent from the selected solutions. Decomposition in sub-functions can be useful to abstract the engineering problem (Pahl et al. 2007). Another visual-oriented approach is the *product family master plan* (PFMP) (Harlou 2006). Large quantities of information are presented on a poster, arranged in customer view, engineering view and part view. The PFMP makes it possible to show several product variants in one single model. The *design structure matrix* (DSM) (Pimmler and Eppinger 1994) decomposes a product into sub-systems and components, and identifies interfaces among these. Sub-systems that are closely interrelated are clustered. Further, the *generic bill of materials* (BOM) (Van Veen and Wortmann 1992) is a key to effectively generate specific BOMs. The generic BOM enables the creation of a specific BOM, when a certain solution is selected. This way, the number of different BOMs is reduced by providing a generic view as an overview. The interface diagram (IFD) (Bruun and Mortensen 2012) is capturing structural characteristics of a system. It maps the system between the domains, and between function and form. Last but not least, model-based systems engineering intends to leverage the output of engineering activities as a model (Friedenthal, Moore, and Steiner 2012) with help of the systems modeling language (SysML). This is a graphical modeling language and supports analysis, specification, design, verification, and validation of any complex systems.

3.4 Needs for Product Portfolio Mapping

All the introduced phenomenon-modeling methods provide views of the product, interfaces, structures, or architectures and combinations of them. However, all approaches assume a virtually new product and are not established for adaption within an existing product environment. They fall short in creating an overview over an existing product portfolio; hence, a different approach to model such an established system needs to be applied. In this paper a new product portfolio map approach, following a reverse path of the steps of engineering design methodology, will be introduced. Beginning with the principal layout and then mapping variances on architectural, functional and physical levels, this enable mapping the product portfolio from a comprehensive engineering view. In addition, an approach to model sub-systems that go across the modules will be presented. Current and future options have been mapped in a simple, visual way, providing maps at both global system and modular levels.

The map of the portfolio, functional and physical structures as well as architectures might serve as a basis to clean up product variances, sharpen the product strategy, and establish a common product architecture that supports a prospective, more knowledge-based approach to effective NPD.

4 APPROACH TO MAP THE PRODUCT PORTFOLIO

In the following, the methods used to create a map of the case company's product portfolio at global system and modular levels will be exemplified following an engineering perspective. The portfolio map illustrates product variants on functional, physical, and architectural levels. Due to confidentiality and secrecy, company, product and customer characteristics are left out of the discussions below. Figures and schematics have been simplified and details, functions, module descriptions, etc. have been encoded to generic terms. Nevertheless, the principal result of the modeling, which is the main outcome of this paper, is still clearly highlighted for general applicability.

Hansen et al. (2012b) define a number of external factors that classify an architecture. These are, among others, market launch clock speed, formal justification, market position, physical constraints, volume per variant, or customization solution space. These factors have been used as a basis to structure the case company's products, and to apply these steps to have a clear architectural initiative:

- Map the external factors of importance;
- Prioritize which factors to take into account;
- Concretize and quantify how to address the factors;
- Design the architecture initiative to respond to the external factors.

Following these basic steps, the most recent products in the company were systematically studied to determine *what* the product delivered in terms of performance, configurations, variants and product properties, along with their associated allowable limits. Moreover, it was examined *how* the technical problems had been solved in terms of functionality, principal solutions, and detailed design. Existing modularization approaches and arrangements of functions and 'function-owners' have been analyzed. A top-down approach has been applied for the analysis, starting with the product at system level and continuing to sub-systems and details. Hence, the established portfolio map, including a structure at functional and physical levels, makes it possible to identify commonalities and differences between existing product variants. Table 1 summarizes the steps that were taken to map the product portfolio. The steps, especially steps 5-8, were done iteratively to achieve satisfying results.

Product deliveries have been systematically analyzed by gathering information from product documentation, PLM systems, and, most important, interviews with engineering domain experts for the sub-systems. Since many variants in product deliveries have been discovered and variants generate costs in all phases of the product life cycle (Hansen et al. 2012a), the reasons for having variants have been detected. In addition, prospective developments and potential future trends for the coming five years have been considered. This gives the possibility to map future solutions in addition to current solutions for related functions.

The quantity of variants made it difficult to identify certain aspects. In particular, it was challenging to determine whether observed differences are real variants, or the same solutions just modeled in another way. Some systems are stable, yet difficult to detect because different types of documentation can show the same system in another interpretation made by the engineer(s) who made it. One common challenge, however, was that some systems are designed to perform tasks across several modules.

A visual, phenomenon approach has been applied below, and the relations of the product portfolio, both within and in between variants, have been visualized. The product portfolio maps have been established using MS Visio, and were printed on posters to provide an overview to the company's engineers across different divisions.

Table 1. Steps to structure the product portfolio

	Step	**Purpose**
1	Analyze delivered products	Identification of modules, Identification of global performance ranges
2	Analyze the external factors	Understand reasons for product solutions and reasons for variants
3	Analyze sub-systems	Understanding system and dependencies; detect key components; identification of variants; identification of modular performance ranges
4	Create performance maps	Establish an overview about delivered and required system properties
5	Interview with accordant sub-system expert	Understand reasons for selected solutions and variants, identification of prospective solutions
6	Model drafts for different structures	Structure the findings of step 1 and 2 and create a base for further work
7	Discuss results of step 3 with accordant sub-system expert	Ensure that system is modeled correctly; critical review
8	Adjust product portfolio map and complete modeling. Establish interface diagrams and roadmap for future launches	Establish a clear overall model of the product and its variants
9	Align with PLM system	Implement structure in the database

5 STRUCTURING PRODUCT VARIANCES IN A PORTFOLIO MAP

Figure 3 shows the arrangement of the product portfolio of the case company in simplified form at different levels of abstractness. The figure tabulates design choices, beginning with the overall layout of the system in the first row, followed by the architecture in the second row. The third and fourth rows illustrate the functional and physical variances. Each row shows a number of variants that follow from the selection made in the row above. The grey arrows between rows symbolize the number of variants provided by the chosen solution. The column on the right summarizes customer inputs and requirements that may affect the selection of a specific variant.

The selection of principal layout in the first row is dependent on superior factors, such as geometry, required power, product environment, etc. In Figure 3 simplified schematics are used due to confidentiality. In the row below, possible options of the principal layout above are listed by the variants A, B,…N., showing the overall system architecture. Common systems that are responsible for main dependencies within the product and important across the variants are displayed as a line going straight through the different options. Hence, the intersection with function blocks within each variant indicates what kind of the common sub systems is the governing factor for the variant’s architecture. Variant C will be considered in the present example.

The third row shows the functional level of variance for architecture variant C. Depending on customer requirements, it is necessary to provide a certain functional variance in addition to the architectural variance. Furthermore, in the third row functions and functional flows are defined. All variants (C_1, C_2,.., C_n) have basically the same main functions, which are displayed by the systems going across the variants, whereas their specific sub-functions to fulfill the main functions are different due to layout or sequence. The latter are caused by different customer desires, safety requirements, etc.

Finally, the bottom row in Figure 3 illustrates the physical variance of the product, dependent on a selection of a principal layout, architectural variant and functional variant. Physical solutions shown in this row perform the functions of the specific variant selected above. Different physical variants to solve the functions of the row above can be selected as a a customer option. Some variants apply integrated design; others use modular design, which divide the system into modules as illustrated by different shadings.

The portfolio map in Figure 3 summarizes the different variants of the system at architectural, functional, physical and layout levels. The visualization scheme makes dependencies, models, and systems across the models visible and transparent at global system level. This engineering view provides a comprehensive product portfolio overview, which can be used as a basis to implement and structure the product in a PLM system, for strategic, architectural commonization, representing a pathway towards a KBD system as introduced in Section 2. The maps can be used to eliminate similar variants and to detect standardization possibilities as well as necessary customization areas.

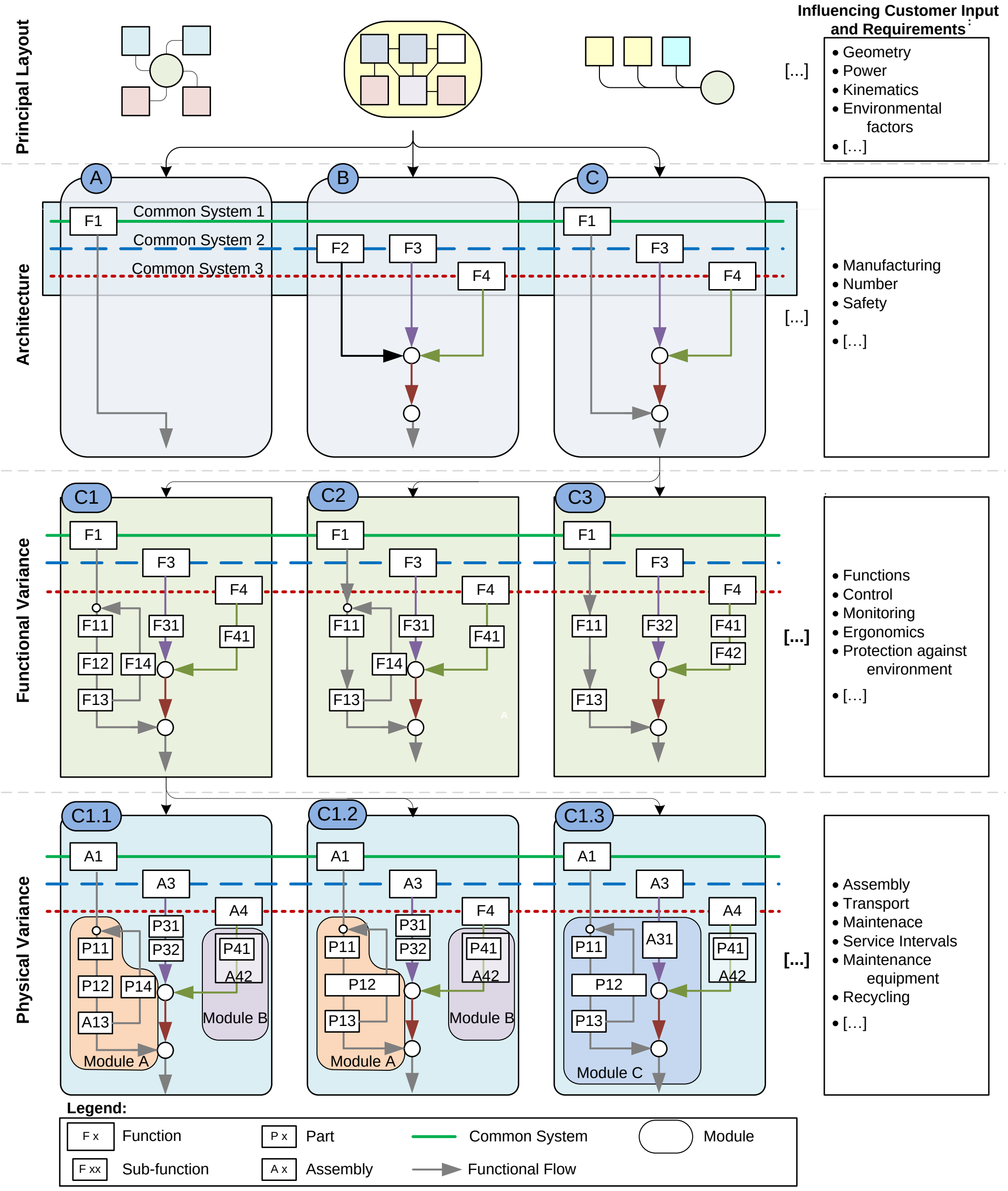

Figure 3. Product Portfolio Map with Functional, Physical, and Architectural Variance

While Figure 3 illustrates the system at a global system level, it is also necessary to consider variants at modular level, including design options for both current and future modules. Standardization of components at lower level is the key to enable flexibility at a higher system level (Sanchez and Collins 2002). In this respect, the modules and their development, along with standard designs and customer specific solutions, were also studied.

Figure 4 illustrates schematically the design options of one module for current (upper half) and future (lower half) options. The figure allocates principal solutions to functions, while the functional structure remains (nearly) stable between the present and the future state, while the principal solutions are changing due to specific efforts in NPD. The principal solutions are illustrated in building block boxes, with a dotted line showing the sub-system boundary. They are linked to a function in the functional structure above. Each sub-system includes a color code, making the modular development more predictable with regard to cost and risk factors that are easier to influence. Once a certain configuration is selected from this diagram, it will be easy to detect parts that require further development or testing or ones that could potentially influence the critical path of the development process. Hence, a visual overview of design options at modular level is provided.

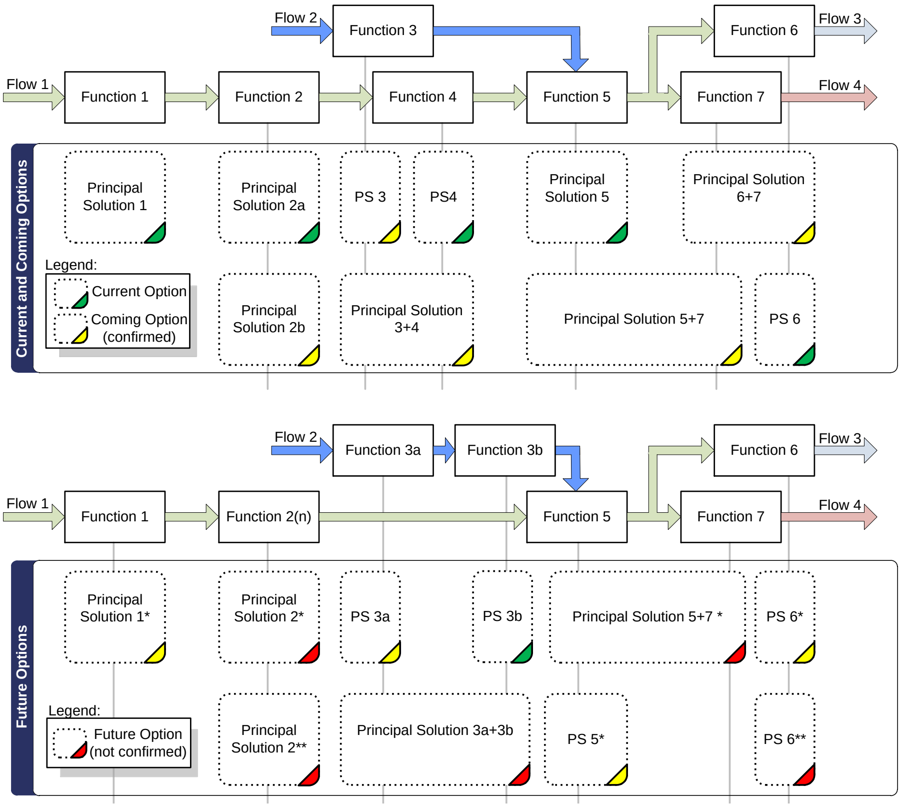

Figure 4. Variant Map for Design Options at Modular Level

6 CONCLUSIONS AND OUTLOOK

The product portfolio map for variants at system level and the map for design options at modular level illustrate how an existing product portfolio can be mapped. Both system level and modular level information, as well as variance at functional, physical, and architectural levels, are considered. Information and knowledge from many different projects are converted into a common framework showing the product portfolio as a whole. Knowledge is visually structured and linked as concrete, abstract building blocks, giving a clear overview of modular interfaces and dependencies. Parallel, visual mapping of variants at different abstraction levels gives a good overview of the complete product portfolio using a portfolio map provided by color coding, and schematic modeling of current and future options.

In further development, the introduced maps need to be used to sharpen und restructure the product portfolio. A common product architecture that is robust and stable over a certain time period, while providing extension for future developments, will be established. It needs to be flexible to accommodate customer wishes, and cover desired performance ranges. Once a new product architecture is established, it may become the backbone of the so-called knowledge-value stream in KBD, supporting visual commonization, continuous improvement and knowledge reuse, where knowledge is linked to the architecture. The structure itself represents knowledge at system level, showing modules and interfaces, dependencies and future options. A further level of knowledge mapping on detail level is mapped for certain components as illustrated in Figure 4. Probably no 'one size-fits-all' solution exists for a product architecture (Hansen et al. 2012a), but the mapping may enable establishing modules and structures that cover a wide range of variants.

One general challenge in leveraging effective knowledge capture and reuse in multi-disciplinary engineering teams is to establish a common language across the different disciplines and systems (Friedenthal, Moore, and Steiner 2012). The visual approach introduced herein is believed to improve communication within the company, between different functional departments and disciplines, and between company and customer as well as with suppliers. For example, an additional customer view could illustrate customers' dependencies of their wants, and thus increase the understanding of implications on product cost and lead time. Finally, the present approach can also provide a baseline for implementation of more transparent product information in PLM type systems.

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