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Complex products and systems: Potential from using layout platforms

ADRIAN P. HOFER[1] AND JOHANNES I.M. HALMAN[2]

[1]Hofer und Partner AG, CH-8002 Zürich, Switzerland
[2]Eindhoven University of Technology, Eindhoven, The Netherlands

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Abstract

In their quest to manage the complexity of offering greater product variety, firms in many industries are considering platform-based development of product families. Key in this approach is the sharing of components, modules, and other assets across a family of products. Current research indicates that companies are often choosing *physical* elements of the product architecture (i.e., components, modules, building blocks) for building platform-based product families. Other sources for platform potential are widely neglected. We argue that for complex products and systems with hierarchic product architectures and considerable freedom in design, a new platform type, the *system layout*, offers important commonality potential. This layout platform standardizes the arrangement of subsystems within the product family. This paper is based on three industry case studies, where a product family based on a common layout could be defined. In combination with segment-specific variety restrictions, this results in an effective, efficient, and flexible positioning of a company's products. The employment of layout platforms leads to substantial complexity reduction, and is the basis for competitive advantage, as it imposes a dominant design on a product family, improves its configurability, and supports effective market segmentation.

Keywords: Complex Products and Systems; Layout Platform; Platform Concept; Product Families

1. INTRODUCTION

In a global, intense, and dynamic competitive environment, the development of new products and processes has become a focal point of attention for many companies. Shrinking product life cycles, increasing international competition, rapidly changing technologies, and customers demanding high variety of options are some of the forces that drive new development processes (Wheelwright & Clark, 1992; Pine, 1993; McGrath, 1995; Ulrich, 1995). To increase their level of competitiveness, many companies have switched their focus from single products to product families to increase the potential for reusing elements from product to product. A growing body of literature advocates the building of platform-based product families to increase efficiency and flexibility in new product development and in order processing (Sanderson & Uzumeri, 1995; Meyer & Lehnerd, 1997; Sawhney, 1998).

Reprint requests to: Adrian P. Hofer, Aubrigstrasse 12, CH-8002 Zürich, Switzerland. E-mail: adrian.hofer@hoferundpartner.ch

We based our research on the platform concept according to Robertson and Ulrich (1998), who define a *platform* as the collection of assets that are shared by a set of products (i.e., a product family). Criteria for platform elements are their high commonality potential, while differentiation needs have to be served by nonplatform elements. This is necessary to reach a high degree of individualization with robust and standardized product architecture elements.

The concept of building product families based on platforms has been widely accepted in literature as an option to create variety economically. The reasons (or expected benefits) of the concept are mainly greater flexibility in product design, efficiency in product development and manufacturing, and effectiveness in market positioning. The application of the platform principles leads to different platform types according to the kind of assets that can be used as a common basis. Sawhney (1998), for example, introduces several platform dimensions (product, process, customer, brand, global). Literature also mentions the substantial risks and trade-offs that have to be made in developing and managing platform based product families (Sanderson &

Uzumeri, 1995; Sanchez & Mahoney, 1996; Meyer & Lehnerd, 1997; Meyer et al., 1997).

Notwithstanding the growing body of literature concerning the platform concept and its application in practice, there is gap when it comes to the application of the platform concept for complex products and systems (CoPS). CoPS have been established as a distinct area of innovation research for products and systems, where a complete decoupling of subsystems is rarely feasible, and the variety of subsystem combinations can cause high levels of uncertainty and risk in system design, production, and integration (Hobday, 1998; Hobday et al., 2000). The architecture of complex systems is characterized by multiple levels of hierarchy (Simon, 1969) and a wide range of architectural choices in system specification. As a result, CoPS are engineered to order (ETO), which causes project-specific system design and engineering efforts and leads to high resource expenditures, time consumption, and project risk. The subsystem interactions of CoPS complicate the identification and realization of reuse potential and system complexity reduction (Hobday, 1998).

As the decisive characteristics of CoPS are their hierarchic structure and their architectural choices, a focal point of our research is on product architecture issues. The fact that product architecture has an essential influence on system complexity and on the design and flexibility of a product family has been pointed out by many authors (Henderson & Clark, 1990; Ulrich, 1995; Yu et al., 1998; Jiao & Tseng, 2000; Krishnan & Ulrich, 2001). We use the term *product architecture* in the definition proposed by Henderson and Clark (1990), who describe it as the way components are integrated and linked together to form a coherent whole (i.e., a system). This definition fits the emphasis of CoPS on systems design, project management, systems engineering and integration, coupled with a high degree of customization (Hobday, 1998). The distinction between the product as a system and the product as a set of components, and the conclusion that successful product development requires two types of knowledge (component knowledge, architectural knowledge) reflects the specific characteristics of CoPS.

The finding that companies often limit their solution space for platform potential to a low hierarchical level of the product architecture (i.e., shared components/modules), resulting in physical *product* platforms, supports our assumption that unused potential in the development and management of platform-based product families exists (Halman et al., 2003). This leads to the question of whether the platform concept can lower overall system complexity through the use of commonality on a hierarchically higher level of the product architecture (i.e., on the level of subsystem arrangement or layout). The search for platform potential in this new area is a necessary completion to our knowledge about the platform concept.

The product architectures of CoPS often combine considerable freedom in subsystem arrangement (i.e., in product layout) with incomplete decoupling of subsystems. As a result, every system requires high, project-specific system integration efforts (i.e., an ETO approach). If system complexity can be efficiently reduced, competitive advantages can be created.

In this paper we introduce a new platform type, the *layout platform*. We define the system layout as the arrangement of its subsystems. Designing a product family based on a layout platform means defining *a priori* (and, therefore, standardizing) the arrangement of subsystems that the product consists of. This standardized arrangement of subsystems is a deliberate restriction of architectural choices and serves as a basis for segment-specific (derivative) product development.

Although the notion that the platform concept comprises tangible and intangible elements shared by a set of products is not new in literature (see, e.g., the platform definition proposed by Robertson & Ulrich, 1998), many case studies focus on products with relatively low levels of complexity. We argue that the deliberate restriction of architectural choices (i.e., through a layout platform) is a powerful means to reducing engineering complexity and risk.

This paper analyzes the use of the platform concept in practice. It investigates how and where platform potential can be identified regarding CoPS, and what trade-offs have to be considered. It looks at how different companies use commonality across products within a product family, and where further (unused) potential can be found. With a focus on product architecture, the paper looks at different hierarchic layers to identify new platform potential. A framework is used to compare and to generalize the findings, and finally to draw conclusions for the design and management of platform based product families.

2. RESEARCH METHODOLOGY

2.1. Research design

The objective of our research was to investigate the application of the platform concept for CoPS in different companies, and to compare how platform and product family concepts are realized in practice. Case study research involves the examination of a phenomenon in its natural setting. The method is especially appropriate for explorative research with a focus on “what” and “how” questions concerning a contemporary set of events (Eisenhardt, 1989). The research design involved multiple cases, generally regarded as a more robust design than a single case study, because the former provides for the observation and analysis of a phenomenon in different settings (Yin, 1994).

2.1.1. Sample

We studied three technology-driven companies. These firms represent a variety of product and market contexts, and provide examples of a range of platform and product family concepts and implementations. The following criteria were used for selecting the firms:

1. companies who sell, design, develop, and manufacture complex products or systems (i.e., product architectures with multiple levels of hierarchy, and architectural choices in product specification); and
2. companies where product or system complexity leads to competitive disadvantage (i.e., difficulties to enter or defend a lower market segment, or inaccessibility of computational methods (e.g., product configurators) because of highly complex relationship knowledge).

2.1.2. Data collection and analysis

The data collection and analysis was carried out in three phases. In the *first phase*, the initial situation of product family management in the case companies was analyzed, covering the market positioning, market structure, product architecture (and variety), and value chain processes. Unused platform potential was identified, a new product family concept was developed, and the platform effects were estimated. These projects had durations of 3–4 months each, and were conducted with a team of experienced people from sales, engineering, research, and development, and manufacturing. The methodology employed is described in Section 2.2. In a *second phase*, based on information gathered during the projects, a framework for structuring case-specific data was developed. This framework (cf. Section 2.3) consists of a common description of the product architecture and of the platform effects. It allows to compare case-specific data and to generalize its results for drawing conclusions to answer the research questions. In the *third phase*, the case-specific data were represented within the framework, and a content analysis was performed to compare and to generalize the research results across the cases and to draw conclusions.

2.2. Methodology employed for identifying layout platforms

The methodology employed in all cases consisted of the following steps: first, the product family architecture was described and different system types (layouts) were classified. Second, the market demand for the defined system types was analyzed based on historic sales data and requirements and trends estimations. Third, the impact of system variety on design dependencies and complexity step was described. Fourth, based on this information, the task was to identify potential layout commonality. This was done in an iterative way through the separation of system types *not* suitable for standardization, and the integration of the remaining system types on a common basis. The two measures employed were the market impact of the resulting product family (where targets were set to fulfill the system requirements of 70–80% of the total market with products based on the layout platform), and the effects on system complexity (where the goal was to reduce design dependencies within the product architecture).

Basis for the identification of platform potential was the product architecture description. It consisted of the following three perspectives: functional variety (classification parameters and their respective value variety), subsystem variety, and design dependencies (or configuration rules) between functional and subsystem variety (Tseng & Jiao, 1998). The design dependencies were used as a measure for overall system complexity.

The definition of the product family and the underlying layout platform was done in an iterative way between alternatives for system layout restriction and the resulting product family definition. The decisive trade-off had to been found between the product family definition (market potential of the family) and the resulting commonalities (layout restriction effects on system complexity). This balancing between customer needs on the demand side and product architecture (or design) choices has also been described by Yu et al. (1998) and Moore et al. (1999).

2.3. Analysis framework

2.3.1. Product architecture (hierarchic layers)

In this paper we are focusing on a specific *layer* of the product architecture of CoPS, the *system layout*, for identifying commonality potential. Several authors emphasize the determining influence of the product architecture on product innovation, manufacturing, and variety (Henderson & Clark, 1990; Krishnan & Ulrich, 2001). Our framework for the description and analysis of the product architecture is based on the characteristic of CoPS to be hierarchically structured (Simon, 1969; Hobday, 1998). We use this hierarchy to identify architectural layers, and then use these layers for the separation of differentiation needs and commonality potential within a product family. Figure 1 shows **Figure 1**
a generic model with four layers: the first layer of the product architecture describes the predefined features and components that form the basic building blocks of a subsystem (i.e., the product platform). The second layer covers the variable functional specification and the resulting physical configuration of the subsystems. These first two layers define the subsystems, which are arranged in a system layout (third layer). The integration of these subsystems to achieve the

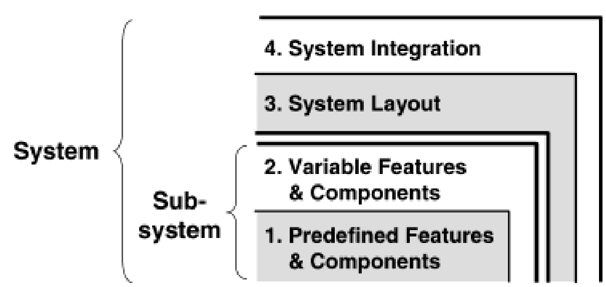

Fig. 1. The hierarchic layers of the product architecture.

desired system functionality and performance is done in the fourth layer of product architecture.

The separation of different hierarchical layers distinguishes physical and conceptual elements of the product architecture. This structures the search for platform potential and allows generalizing and comparing the findings over multiple cases.

2.3.2. Platform effects

Our framework for the description and comparison of the effects of platform-based product families consists of the following three dimensions (Belz et al., 1997): the effectiveness of the product family positioning (differentiation), the flexibility of the product family design (responsiveness), and the efficiency of the resources used within the product family realization. These elements and criteria form the research framework that was applied to the case studies.

Product family positioning covers the *communication* of the product range to the market and within the company and in its value chain. Its task is the realization of the chosen competitive strategy and the (segment-specific) effective differentiation of the product range within the family. The communication towards markets and customers focuses on segment-specific clusters of products that are based on the same platform (and thus represent a product family), but that are positioned differently. Criteria for the effectiveness are the positioning in the market (realization of the competitive strategy), and the ability of a product family to support effective *market segmentation*.

Product family design consists of the definition and the design of the product range offered in the market within the family. In a situation with a broad product range (high variety), and increasing adaptation time and costs, the value of flexibility in the use of resources becomes increasingly important (Sanchez & Mahoney, 1996). Goal of the platform approach is the flexibility of the product family design (i.e., the variation potential of single products and the adaptation potential of the whole product family) over its life cycle. This effect is influenced to a large extent by the product architecture. Increasing variation and dynamic requirements are caused not only by technological change, but also by varying customer needs and competitive relationships. The flexibility of product family design determines the management of an uncertain environment and holds an important position in variety management. Or expressed differently: “Without uncertainty there is no need for flexibility” (Kogut & Kulatilaka, 1994). The criterion for the flexibility of the product family design is the ability to impose a *dominant design* to combine product and process innovation on a product family level.

Elements of *product family realization* are the order *neutral* (advance) platform development and the order-*specific* processing within the value chain (order handling, product specification, engineering, and manufacturing) (McGrath, 1995). The time- and cost-efficient organization of its business processes is a key competitive factor of a company. The goal of product family realization is the efficient use of (limited) resources and time because of increased reusability. The effects of the platform concept can thus be described by analyzing the efficiency of product family realization. Meyer and Lehnerd (1997) use cost and time expenditures for product design and production as criteria for the evaluation of the platform concept.

3. CASE STUDIES

In the following, the three companies contributing to the case studies are characterized. The first company, a provider of postprint management systems (case PPM), is a global player in a specialized market with 850 employees. The second company is one of the world’s largest providers of railway vehicles (electrolocomotives, case ELO), and employs 20,000 people with a sales volume of 3.5 billion EUR. The third company produces wires and cables for energy and signal transmission (case EST) with 1000 employees and sales of 150 million EUR.

3.1. Initial situation

The three cases represent different markets, products, and applications. However, common to all three companies is a market structure with different market segments. The analysis also found a similar structure of product architecture layers across all cases, where existing platform concepts were in use to increase commonality on a hierarchically low (component or assembly) level. These product platforms have no substantial limiting effect on system complexity, as they do not restrict subsystem interactions, and consequently, cannot prevent high system integration efforts. This complexity prohibits entering lower market segments.

Table 1 compares and summarizes the layers of the product architecture found in the three cass. **Table 1**

3.1.1. Case PPM

PPM comprises the transport and storage of rotary press output, the inserting of supplements, and the packaging, addressing, and distribution of finished products (i.e., newspapers with inserts). The company was initially focused on the upper end market with high demands on system performance. The inserting system receives the print output from the rotary press or a storage system on a conveyor belt, completes them with *inserts* (e.g., ads), and passes them on for addressing and packaging. The capability for system expansion through the connection of several inserting lines is a central quality of the product family. Existing systems can be adapted to changing functional or capacity needs. As a means of investment protection for customers this results in a high customer tie. The systems are specified to individual operation concepts with high engineering efforts caused by special customer demands and high efforts to integrate external systems or components.

Table 1. *Layers of the product architecture*

Layers	Case PPM	Case ELO	Case EST
1: Predefined features & components	Basic subsystems built on predefined building blocks e.g., insert drum)	Standardized assemblies with basic functionality (e.g., converter)	Standardized & prefabricated lead components (wires, coat material)
2: Variable features & components	Options on assembly or system level (e.g., transport speed)	Customer-specific specification & add-ons (e.g., frequency)	Options (wall thickness, color)
3: System layout	Arrangement of assemblies (depending on backup functions, number of transport lines, etc.)	Arrangement of assemblies depending on assembly measurements, & machine room size	Lead construction (combination of wires & coating to leads)
4: System integration	Control system for inserting, transport, & integration of outside systems (e.g., packaging, storage)	Control system for locomotive, cabling, & piping of all assemblies within system	Cable construction (combination of leads & coating to cables)

The market for PPM is dominated by few rivals. It can be divided into a segment for highly individualized solutions, a segment with a predefined (configurable) product range, and a segment for standardized solutions in a lower level. The strategic goal of the company is to build a strong competitive position in the lower price (but high-volume) market segment. Many efforts to enter the lower price segment with the existing systems approach proved unsuccessful because of difficulties in realizing concept or design reuse potential. The lack of a common platform for different market applications led to high individual engineering efforts and intensified the danger of getting pushed into an increasingly narrow market niche.

The systems are built of different subsystems or assemblies (with functional options), which are arranged in a specific layout and integrated in the surrounding systems (rotary press, addressing, and packaging). The layers of the product architecture consist of basic subsystems (assemblies based on product platforms) with standard functionality, variable features, and components (add-ons), the layout (arrangement and connection of the assemblies), and the system integration. Each layer with its specific variety leads to increased complexity in controls and operations design and cost of commissioning and testing.

The analysis of the product architecture showed high levels of variety with comparatively low effects on segment-specific differentiation resulting in high process complexity in all market segments. Although the modular product architecture on the assembly level resulted in a high degree of *component* reuse, reuse on the system level could not be consistently realized from project to project. Especially the customer-specific design of the system layout results in high levels of detail engineering, and increases project costs and risks.

3.1.2. Case ELO

Locomotives are traditionally specified and built to order, whereas the lack of a common basis inhibits an effective reuse of components and modules. The high-order specific efforts result in a poor cost position, in particular in the case of small lot sizes. To be able to keep pace with price evolution, a high degree of reuse and a substantial reduction of engineering efforts is necessary. Because of these general conditions it is getting increasingly difficult on the one hand to speed up the order processing with a differentiated order, and on the other hand, to fulfill the cost targets to maintain the market share. Reaching the profitability targets with medium and small lot sizes can only be achieved through the reduction of engineering and order processing efforts and through the reuse of existing solution elements.

The market for railway vehicles is exposed to strong structural changes. Through the privatization of formerly state-supported railroad companies and the ceasing of subsidies the price sensitivity of the customers increased substantially. The entire market is characterized by excess capacities, which lead to decreasing unit prices. The market price for electric locomotives up to 6.4 MW has dropped by around 30–40% from 1990 to 1997. Simultaneously, the purchase behavior changes and lot sizes decrease dramatically.

The product architecture of electric locomotives consists of different layers: standardized system assemblies (building blocks, i.e., product platforms) with basic functionality; customer-specific system features and assemblies; the arrangement of the assemblies in the engine room; and the integration in the overall system (locomotive).

The virtually unrestricted variety on the assembly level leads to high integration complexity and risk, and consequently, to a critical cost position for realizing small to medium lot sizes (too high engineering costs per locomotive). The building of assemblies based on physical platform components has some effects of scale on the assembly level but cannot substantially lower complexity in system integration.

3.1.3. Case EST

The company providing wires and cables for EST offers its products in three vertical market segments: standard products, which are listed in the product catalog; configurable products from standard components; and technically demanding special products that have to be engineered individually.

The company positions itself through the development competence of solutions for specific customer needs, for example, in automobile manufacturing. Although in this segment a high level of development effort for specific products is accepted and paid for by the customers, the ability for rapid and low-cost reaction (flexibility) in a lower market segment (mass customizing) becomes increasingly important. In a market environment characterized by time and cost pressure, high response times for offer creation and order processing represent a competitive disadvantage. Customers with needs very near the catalog product range hardly understand these delays and are not willing to pay extensive development and testing activities.

Cables are built of single wires that are twisted to a conductor and then coated (extruded) with insulating material of specified thickness and color. Cables consist of a combination of leads that are coated again. The elements (layers) of the product architecture are: predefined lead components (wires, coating materials), variable subsystem features (wall-thickness and color), the lead construction, and the cable construction. These layers also reflect the production process.

The low degree of interaction between the components leads to almost unlimited variety, because few (technical) restrictions exist. As a result, orders for customized solutions have to be checked for feasibility, and their processing becomes extremely complex and slow. This is accentuated by the need for producing and testing prototypes in many cases, because the almost unrestricted technical variety prevents the precise deduction of product characteristics.

In the initial situation, the different market segments could not be provided with segment-specific solutions, and as a result, the cost position in the basic market was too high.

3.2. New product family concept

Starting from a situation where the use of commonality is limited to a low hierarchical level in the product architecture, the question arises whether new platform potential can be found in other layers of the product architecture. The traditional platform approach focuses on the component level, and mainly affects direct material and labor cost through improved economies of scale. These effects are not always sufficient to support a product range for multiple market segments, as complexity along the value chain is not substantially reduced by this platform approach.

The typical characteristics of CoPS are their hierarchic product architecture and the freedom in architectural choices that lead to considerable complexity and risk in design, engineering, and manufacturing. In the case study projects, the search for new platform potential was thus extended to other layers of the product architecture. As a first step, these layers were identified and then they were separately characterized by their differentiation needs and commonality potential. The overall goal was to realize a segment-specific product range based on a common basis, and supporting distinct processes and process cost. The basic idea of using the platform concept was to search for commonality potential across all market segments with the goal to increase the reusability of concepts especially in the low-end market. The focus in all cases was on using a standardized system layout (arrangement of components or assemblies) as a conceptual platform.

In all three cases it was possible to identify platform potential on a hierarchically higher level of the product architecture. Commonality on a low level (components, assemblies) was already used by all companies. The decisive difference between traditional product platforms and the (new) layout platforms is the degree of influence they have on system and process complexity.

The definition of the different layers of the product architecture resulted in much clearer structured product ranges. The identified commonality potential on multiple layers of the product architecture (product and layout platform) is a basis for segment-specific product differentiation, as shown in Table 2. **Table 2**

3.2.1. Case PPM

The analysis showed that two layers of the product architecture with a high commonality potential could be identified. The new concept is based on the commonality potential on the *assembly* and on the *layout* level, whereas segment-specific functional options and system integration allow for differentiation. The platforms of the product family are the standardized assemblies (product platform) and the standard arrangement of these assemblies (layout platform).

Figure 2 shows the layout platform as the basic arrangement of assemblies. It is highly decoupled from functional options and from system integration by coping with a standardized input and providing a standardized output of material and information flow. **Figure 2**

The definition of the layout platform was based on the coordinated requirements from the respective viewpoints of sales/marketing, development, production, and system integration. The layout is designed as a functionally maximum solution that can be *reduced* (defined elements can be removed) according to order specific requirements.

Table 2. *Results of product architecture analysis and identified platform potential*

Layers	Product Architecture Analysis	Platform Potential
1: Predefined features & components	Range of assemblies (or components) with high variety & a high degree of decoupling	Commonality potential is already used = component systems, product platform
2: Variable features & components	No segment-specific differentiation of functional variety, some options lead to high complexity and risks	High differentiation needs → No general standardization, but → Segment specific rules/restrictions
3: System layout	No standardized layout(s), project specific design & engineering (even for small deviations from standard)	Identified platform potential – System layout (case PPM) – Machine room layout (case ELO) – Lead construction (case EST)
4: System integration	In consequence high system complexity & integration efforts for most systems, no segment-specific rules/restrictions	High differentiation needs → No general standardization, but → Segment specific rules/restrictions

The product family concept supports the chosen market strategy by providing a segment-specific product range that is based on the efficient reuse of platform elements. The layout platform serves as a robust basis for system design and engineering in different market segments. It facilitates the efficient variation without increasing complexity, and at the same time enables the company to design a high tech (and high cost) system for the higher market segment while employing economies of substitution.

3.2.2. *Case ELO*

The analysis of the product architecture showed that two of the four layers offered substantial commonality potential. The commonality potential consists on the one hand of assemblies and components with low variety and a high degree of robustness and stability towards market demand and technology change. These assemblies are mainly in the life cycle stage of dominant design and offer high standardization potential. On the other hand, the layout of the engine room (which determines the assemblies as well as their interfaces and geometrical measurements) could also be standardized.

The new product family concept was based on an existing product platform on the assembly level, and the standardization of the arrangement of these assemblies in the engine room (layout platform). Elements with a high differentiation potential, high-tech units with a short life cycle (e.g., power converters), segment- and customer-specific options (e.g., communication systems), elements for the integration of the units to the overall system (cables, piping system) and the design of the exterior cover did not become standardized but were modularized to a large extent. With that the company managed to reduce the effects of combinatorial complexity.

Figure 3 Figure 3 shows the *layout of the engine room* as a common basis for the whole product family of electric locomotives. This platform defines the arrangement of all assemblies in the machine room, as well as their interfaces and enforces the realization of different product variants within an identical layout.

The definition and development of the engine room layout was only feasible through the application of newest technology for miniaturizing (and standardizing) the assembly sizes to fit within the restricted space of the engine room. The common layout is the basis for subsystem interfaces standardization. The assemblies are always positioned in the same place; cabling and piping between the assemblies runs in the same guide rails. It is possible to install one, two, and multifrequency systems in locomotives with the same engine room measurements. Thanks to small power converters, additional train control systems can be included without having to enlarge a four-axle locomotive for the multi system types.

3.2.3. *Case EST*

The product architecture analysis resulted in two different layers with high commonality potential. All products within the product family were based on a range of standardized components, and a common lead construction, which defines the arrangement (layout) of wires (cf. Fig. 4). **Figure 4**
This leaves the coating material, thickness, and the color as variable differentiation elements. A component system further supports the selection of wires and coating materials, and segment-specific selection rules were defined for the variety of coating material, wall thickness, and color.

The platform definition was based on an analysis of the current product range, and the identification of elements with a high potential for standardization. The standardization of the lead construction proved in this case considerably simpler than the restriction of the isolation materials, where compromises between cost, performance, and manufacturing aspects had to be found. In addition, overengineering could not always be prevented to ensure product family evolution.

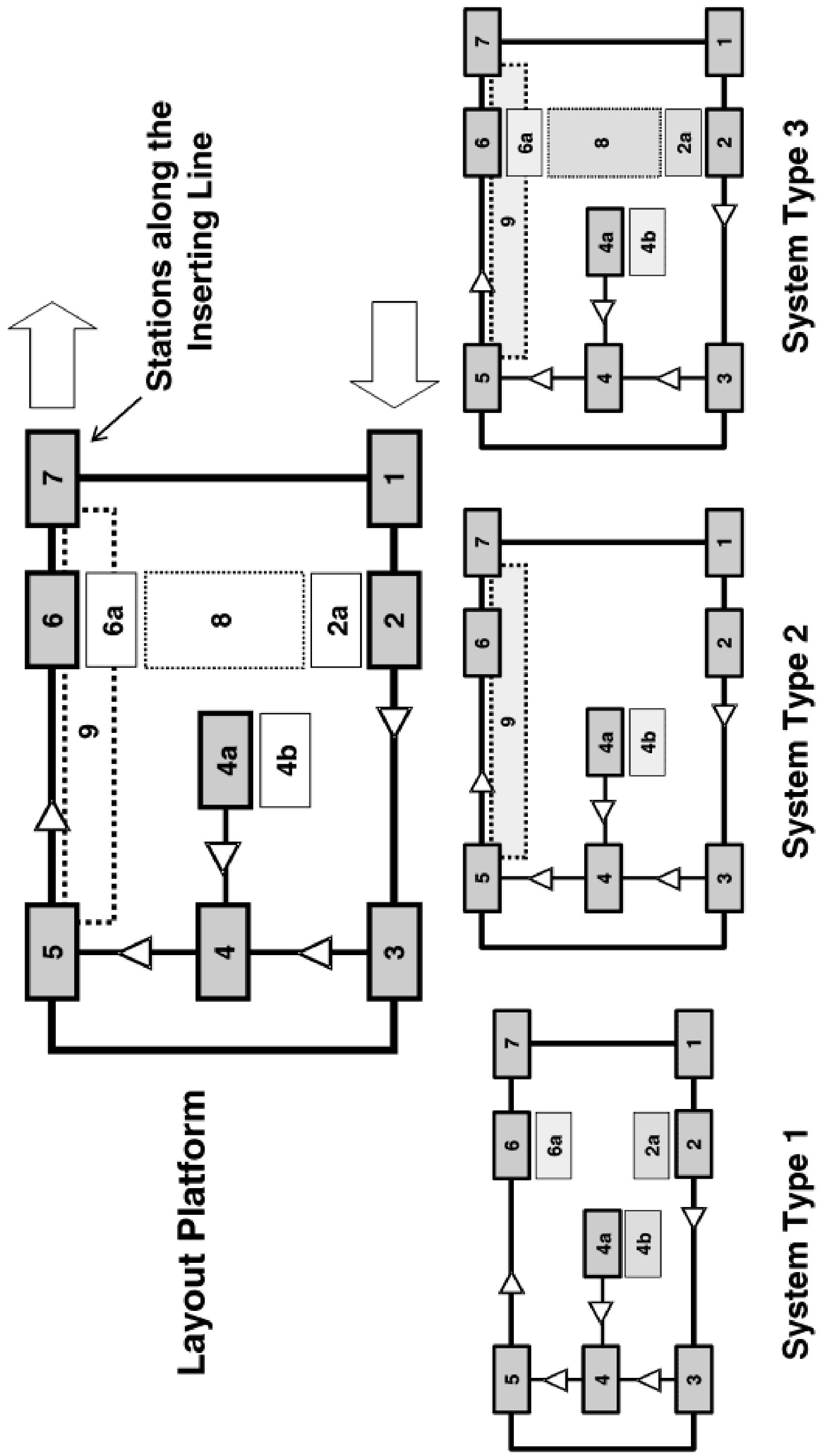

Fig. 2. The standardized system layout as a platform (case PPM).

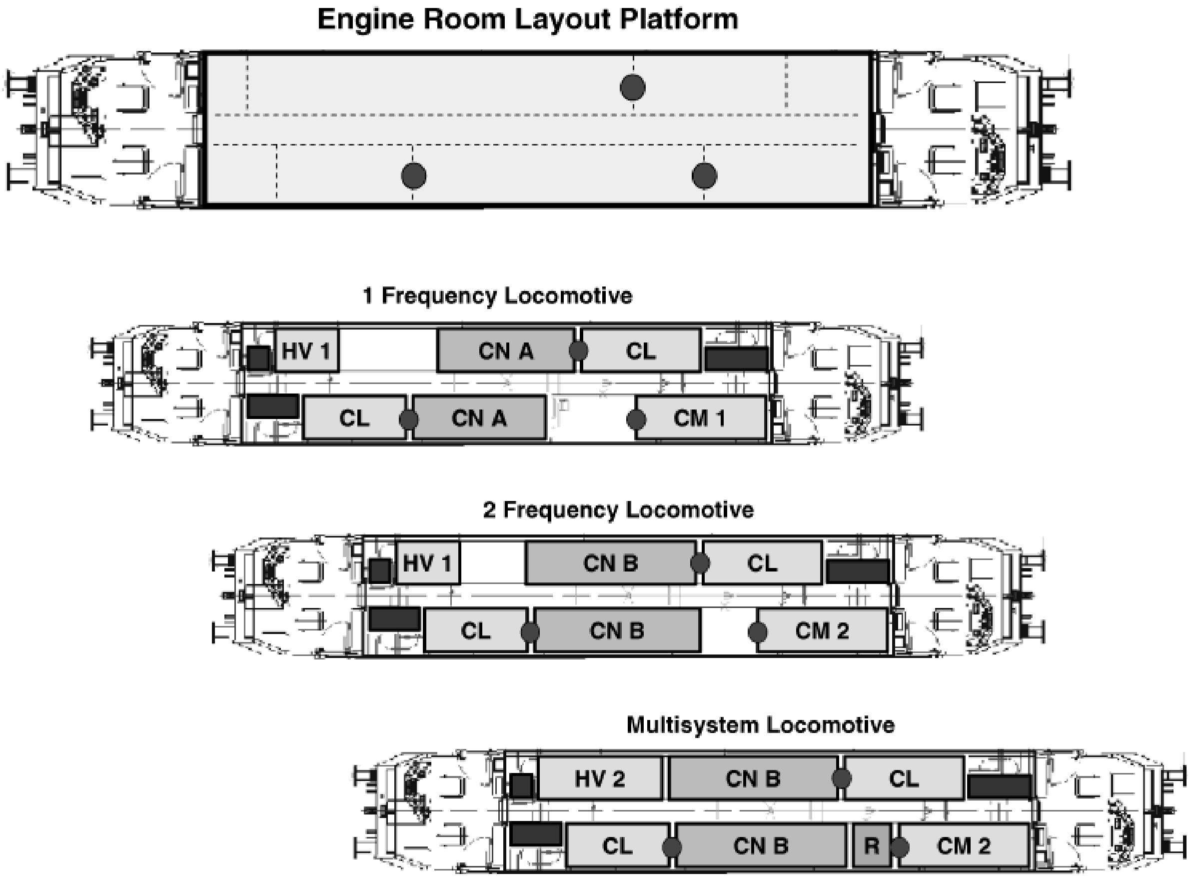

Fig. 3. The standardized engine room layout as a platform (case ELO).

The layout platform defines the arrangement of wires to leads and decouples the leads from other layers of the product architecture. This lowers complexity in the product range that is needed for easy variation of the end-product within tight limits. The so-defined leads can be produced in a standardized process and kept on stock, before being processed to customized cables.

3.3. Effects of layout platforms

3.3.1. Case PPM

From 98 sold systems (based on 18 different layouts), 81 systems (82%) were found to fit within the restrictions of the standardized layout without affecting customer specifications or cost targets. As a consequence, the number of features needed to specify the system's total 15 subsystems could be reduced by 40% from 67 to 40. Within the restriction of the standardized layout, this results in a limited variety of subsystems that has to be considered for the design of systems based on this standardized layout because of the reduction of design dependencies.

In the low-end market segment, the selection of only a few standardized, preengineered options is allowed, and the integration of the system is limited to a standard concept that prohibits the interconnection of multiple systems. In the middle market segment a greater variation of predefined options is offered. The system integration is done within the boundaries of a decision tree that covers the possibilities of the existing operation control system. In the high-end (individual) segment the full range of solutions is offered with considerable efforts in the specification and realization of the system. The design of segment-specific systems is the key to entering the low-end market with a restricted range of products, and within clearly defined cost targets.

Product engineering profits from the complexity reduction through the layout platform. The standardization of the subsystem arrangement allows the technical configuration of the overall system. This facilitates the functional description of the orders as the products are determined within the standard layout, and it supports the integration of controls systems. The order processing can be designed in a segment-specific way. This helps to realize substantial time and cost savings potential in the low-end market segment through lower efforts for system specification, engineering, and installation, and simultaneously lowers the order risk in this market segment. The segment-specific product range leads

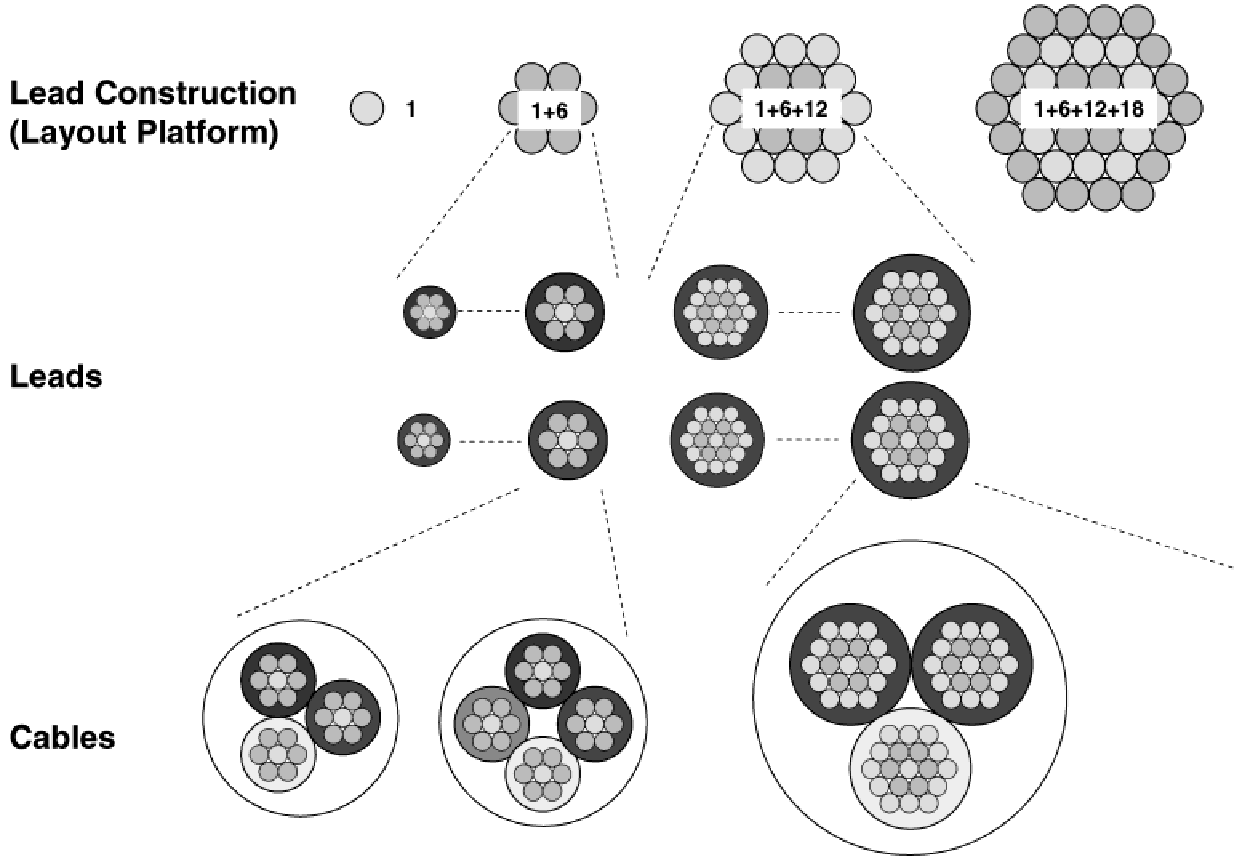

Fig. 4. The standard lead construction as a layout platform (case EST).

generally to differentiated processes and resource utilization. The resources saved through lower complexity in the low-end segment can be used for the more demanding handling of added-value tasks in the high-end (individual) segment. The reuse of existing concepts is furthermore a means to achieve scale effects and to increase planning reliability in procurement and production.

3.3.2. *Case ELO*

As a result of the standardized machine room layout, the feature set for specifying the complete system (locomotive) could be reduced from 357 by more than half to 184 features, while still fulfilling the requirements of 80% of the expected sales volume. The variety of 12 (from total 20) assemblies could be reduced from 1000s to between 4 and 72 assembly types because of fewer design dependencies.

The standard segment provides the basic versions of the locomotives and covers the low-cost part of the volume market with standard and preengineered solutions. The customized segment offers planned deviations from the basic design with a restricted variety of options. In the individual (high-end) segment locomotives are being engineered as individual solutions with performance characteristics at the edge of technological boundaries.

The standardization of the engine room increases the flexibility of the remaining elements of the product architecture through the clear definition of interfaces and the restriction of order specific changes. The necessary flexibility for the realization of customer requirements is guaranteed by the variation of subsystems with high differentiation effects. In the same way the evolution of high-tech elements (e.g., power converters and train control systems) is ensured. The platform concept guides the development of the product family within the set boundaries while keeping considerable freedom in the customer-specific design.

The layout platform serves as a robust basis for different locomotive types and allows the integration of custom-built components. As a result, a locomotive is built to the greatest extent from standard modules, and custom-made changes are limited to a few (isolated) modules. Furthermore, the configuration of a locomotive allows the selection of existing modules and their reuse (within the standard layout and interfaces). The modular product architecture bypasses the disadvantages of small lot sizes through the use of identical modules in different locomotive models. Standardized interfaces allow for the flexible adaptation of the locomotive to modified mission profiles to minimize the operating costs (energy efficiency). This reduces the time and costs of order-specific engineering, increases product quality, and lowers the efforts for assembly and testing. At the same time the layout serves as a robust basis for the development and integration of high-tech components.

3.3.3. *Case EST*

Of 30 different lead constructions (serving as the basis for 213 lead types), 12 could be combined in a standardized system layout (based on a common set of design rules) covering 45 of the lead types and 75% of the sales volume. At the same time, the number of wire types (components for leads) could be reduced by 72% from 232 to 63.

The segment-specific definition of both the product range and the value chain processes enables a differentiated and effective positioning in the market. Market communication can be focused on the differentiating elements, which results in highly effective market segmentation. Customers who find their products in a catalog can order them directly, whereas customers with needs not diverging too far from the standard are being served by a configurable solution. This frees valuable development resources to handle orders with special requirements. The processes for catalog sale, configuration, and construction are distinctly different, and cause segment-specific costs and time expenditures. The use of a component system with defined combination rules represents a further segment-specific restriction of the product range.

The product family design is limited by the standardization of the lead construction (layout platform), and the choice of wires and coating materials. If a customer requests a change of one of these elements, it cannot be realized within the framework of the product family. This conscious suppression of selected variation possibilities ensures that the product family is not subjected to uncontrolled increase of variety. By the definition of component variety and design rules, the product range gains configurability because the necessary relationship knowledge can be efficiently defined. The components with differentiation functions (wires, leads, isolation) enable a high degree of flexibility in the design of leads and cables.

The product realization gains by the definition of the product families on platforms insofar, as no order-specific development efforts result from the configuration of leads and cables within the defined boundaries of the product family. Consequently, more resources are available for the processing of demanding and value-adding development tasks. In the end, by the allocation of development resources to technically complex inquiries, the processing time can be lowered. The specification of configurable products can be used as an efficient way to develop an initial set of prototypes. In many cases one of the prototypes already fulfills the customer needs, and consequently, considerable cost and time savings can so be realized with low technical risk.

The platform concept has also significant influence on order processing. It allows the distinction of segment-specific order types with different processing efforts. The configuration of products helps to increase the process quality, capacity, and speed in order processing. Instead of a response time of up to 3 weeks for customized cables, offers for products within the configurable range can be handled within 2 working days. The fast reaction to offer requests improves the offer success rate and results in higher sales volume.

4. DISCUSSION

4.1. Generalized layout platform potential

4.1.1. *Product family positioning: Enable market segmentation*

The layout platform supports the effective *positioning* of the product family in the market. Because the system layout (arrangement of the assemblies) is *standardized* across all market segments, it is not subject to customer-specific specification and is decoupled from the differentiating elements. It is employed for the description of possibilities to extend a system through the use of additional elements *within* the standard layout. Building up on a standardized basis, the product range can be positioned in a *segment-specific* way. The differentiation of the segments occurs through functional options and the system integration, subjected to segment-specific rules. The product ranges for the individual segments represent a specific *combination* of individual and standardized layers of the product architecture.

Competitive advantage can be achieved by the optimal combination of individualization and standardization. The layouts in the case examples are standardized across all segments, whereas the differentiation aspects are met by the other layers of the product architecture. This allows a segment-specific design of the product range. The market segments are characterized by different levels of variety restriction, thus providing the basis for differentiation in the high-end (individual) market segment through high-performance solutions, in the middle (customized) market segment through efficient variety, and in the low-end market segment through low-cost and highly standardized solutions (Table 3). **Table 3**

The segment-specific definition of the product range allows the effective communication both within and outside the company. It represents a means of variety management by efficiently offering a specifically variable product range to different demand clusters in the market. It fulfills an important communication function through the clear communication of boundaries for system variety and directs development efforts within the framework of the product family.

4.1.2. *Product family design: Imposing a dominant design*

The product family design is limited by the layout platform. The standardized layout forms a stable basis for the

Table 3. *Segment-specific effects of layout platforms*

Market Segment	Standardized Solutions	Customized Solutions	Individual Solutions
Product range	Standard systems, preferred types, restricted range	Configured systems, preengineered types, predefined range	Individual systems, special solutions, unrestricted range
Variety	Basic design, restricted variety, product catalog	Derivative design, customized variety, predefined solutions	Individual design, unlimited variety
Platform	Standardized layout	Standardized layout	Standardized layout as basis, variation possible
Processes	No order-specific integration efforts, limited engineering, solution picking	Low (predefined) integration efforts, low-risk engineering, solution configuration	High system integration efforts (engineering) individual engineering, solution engineering
Positioning	Cost advantages	Efficient variety	High-end solutions

development and realization of the entire product family and defines the design options of the product family to a large extent. The platform limits the innovation capability, and the challenge is to define these restrictions to have as little influence as possible on the rest of the product architecture. The most important requirement for the definition of a layout platform is the possibility for its decoupling within the product architecture to achieve independence from changes within the product family (robustness). This is done by limiting the variety of subsystem arrangements to facilitate the integration of elements with differentiating attributes.

The layout platform is a prerequisite for building systems on existing elements (reusability) while lowering overall system complexity. This results in greater flexibility in a *narrower* defined field. By building a product family on a common (stable) layout, the remaining elements can be rapidly adapted to variable needs. Within the boundaries of the standardized layout and the product family, the potential for efficient variation increases. The structuring of product architecture limitations and options can be used as a framework for the distinction of existing (predefined) and new solutions, and for directing future development efforts.

The case examples show that commonality potential can be realized on different layers of the product architecture within a product family. The layout platform has a distinct influence on product variety and complexity, and it restricts product design flexibility and innovation capability to the subsystem level. The layout platform appears to be an effective basis for the definition of subsystem variety and facilitates the standardization of subsystem interfaces. However, in cases where the layout proves to be an important element for product variation and differentiation, this platform type will not be suitable.

In the life cycle framework according to Utterback (1994), *product innovation* leads to the emergence of a dominant design, which then is the basis for improving efficiency through *process innovation*. A central characteristic of the layout platform is that is has the potential to impose a dominant design on a product family, and consequently, lead to lower complexity and increased process efficiency.

4.1.3. Product family realization: Increasing configurability

Products based on a layout platform can profit from a more rapid and less risky development and production. The platform concept allows the efficient product specification and order processing through the advance investment of platform development. The development of the platform as advance investment for the design of the product range can be high, but as a consequence, the derivative products can be developed and produced more efficiently (in shorter time and to lower cost). The platform has a high leverage effect, as is allows the variation and derivation of products to incremental cost and time, compared with the development of the platform itself (Meyer et al., 1997). Through the reuse of platforms, companies can substantially lower the time and the risk for the development of derived products (Sawhney, 1998).

The striking advantage of layout platforms is that for a complex product it is comparably easier to standardize the *arrangement* of its subsystems than to standardize these subsystems. A layout platform seems especially suitable for *redesigning* product architectures of *existing* products by supporting the reuse of developed elements within a clearly structured framework (layout). In the case studies, their effects were considered less on direct material and labor cost, but on the whole chain of order processing by reducing process complexity cost.

Svensson and Barfod (2002) define several degrees of mass customization (design, manufacturing, assembly, distribution) between the extremes of pure standardization and customization. Our approach for CoPS focuses on increasing the reusability within product families on the design level. The overall effect of layout standardization allows the product family to make a step from highly customized

ETO processes (with architectural freedom) to a more mass customization approach (with a standardized system layout).

The development of a layout platform is useful in cases where the unrestricted combination of subsystems causes high levels of complexity, and the restriction on the layout level clusters solutions with comparable (and lower) complexity. As a result, products based on this layout can be realized with low design and engineering efforts. By standardizing the system layout, the design dependencies between and within the subsystems can be reduced substantially. Lower complexity in the mapping of functional specification to system elements leads to increased configurability of the systems. The system description, consisting of the product family architecture (structure) and the design dependencies (set of rules) used for the identification of platform potential is the basis for a product model for the formal representation of product design (configuration) knowledge (Forza & Salvador, 2002). The product family can be modeled as a configuration type, whereas the functional and subsystem descriptions form the set of predefined system elements and combination restrictions (Soininen et al., 1998). This representation of product knowledge is facilitated by the layout standardization.

4.2. Applicability of layout platforms

The platform effects discussed in the preceding section can be summarized in the tension field between the demands for *variation* and for *innovation*. Sanderson and Uzumeri
?1? (1997) identify this as an elementary trade-off, in which companies must use their limited resources (development resources, budgets, technology options).

Sanchez and Mahoney (1996) describe product design as kind of controlled innovation in which companies create new products through the application of existing and new knowledge about components and interfaces. To make this knowledge reusable, the architecture of the products as well as the functions of the components and their interfaces have to be known. Innovation is thus based on the creation of new information about components and learning about the interfaces and configurability of these components through the possibilities of the product architecture. These differences can be shown in the innovation typology by Henderson and Clark (1990), where they complement the traditional separation into *radical* and *incremental* innovation, and distinguish between modifications of *components* and modifications of the *interfaces* between these components. Innovations on the component level and on the interface level have different effects on competition, and need different organizations for their realization. In the case of CoPS, considerable reuse potential on the architectural level exists and can be employed for lowering complexity and risk in system design, engineering, and manufacturing. The restriction of architectural choices, however, limits the innovation capability to the subsystem level.

A *product platform* standardizes a defined part of the physical elements of the product architecture and their interfaces to the nonplatform elements. This platform type influences mainly direct (material and labor) costs through improving the reusability of the platform elements. It is suitable when achieving efficiency and scale effects with simultaneously short processing times is the main focus. The definition and development of a product platform requires a high degree of standardized functions and elements as well as the continued stability of the platform.

A layout platform standardizes the conceptual arrangement of subsystems. This has a strong influence on system complexity as it decouples different layers of the product architecture. It proves specifically suitable for the integration of complex systems (with multiple product architecture layers), and it affects the complexity and resource utilization of order processing. It is a means for the coordination of different functions and can be useful in particular for the realization of systems with small lot sizes and incompletely decoupled subsystems that cause complexity in system integration. The layout platform can lower system complexity and affects process efforts and cost in design, engineering, and manufacturing.

The different effects of different platform types can be used to support the segment-specific positioning of a product family (cf. Fig. 5). The combination of different platform types with their specific effects, and the segment-specific definition of variety for nonstandard layers of the product architecture allows for effective differentiation between market segments. **Figure 5**

However, there are several limitations to consider when deciding for or against the standardization of system layouts. A layout platform is not suitable in cases, where the variation of the layout is necessary for system performance of product family evolution, the variation of layouts has no critical impact on system complexity (i.e., through the decoupling of subsystems), and the variation of layouts is essential for differentiation and market demand aspects.

5. CONCLUSION

CoPSs have been widely neglected in the research and discussion of platform concepts. The fact that these products are developed and manufactured in single projects or small lot sizes makes the identification and realization of reuse potential difficult and challenging. Incomplete decoupling of subsystems leads to high system integration efforts and to a low level of commonality effects from product to product.

We introduce the layout platform as a powerful instrument in managing CoPS. The standardization of the system layout is a suitable way to reducing system complexity and engineering risk in systems with multiple hierarchic layers of their product architecture, wide architectural choices in design, and strong influences of system layout variety on product and process complexity.

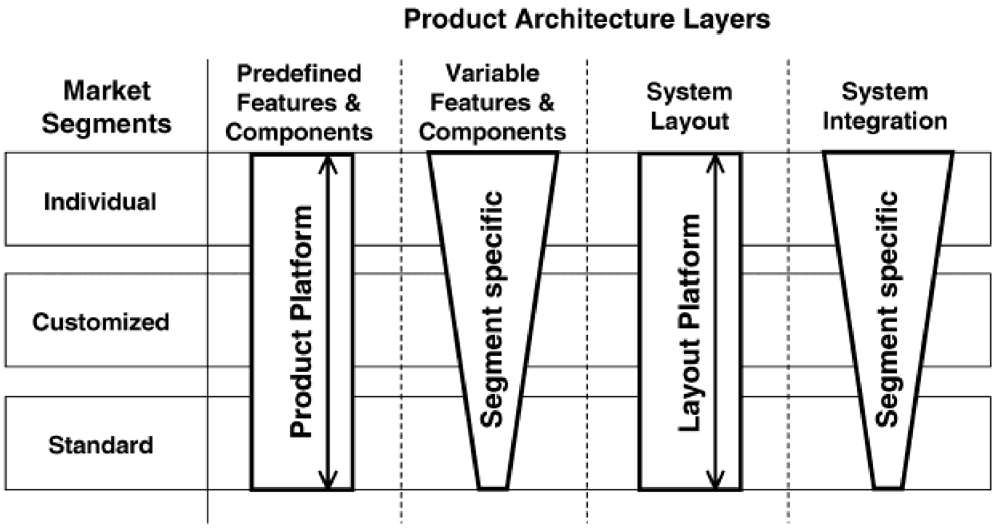

Fig. 5. The segment-specific variety of product architecture layers.

The description of the effects of the platform concept on the elements of product family management and on the product range shows that different compromises about the development of platforms with regard to the flexibility of product family design, the efficiency of product realization, and the effectiveness of product positioning have to be taken into account.

We argue that building a product family based on a layout platform is a powerful strategy for reaching mass customization in case of CoPS. Combined with the segment-specific restriction of the product family, different market segments can be served while retaining effective differentiation.

REFERENCES

Baldwin, C.Y., & Clark, K.B. (1997). Managing in an age of modularity. *Harvard Business Review 75(5)*, 84–93. ?2?

Belz, C., Schuh, G., Groos, S.A., & Reinecke, S. (1997). *Industrie als Dienstleister*. St. Gallen, Switzerland: Thexis.

Eisenhardt, K. (1989). Building theories from case study research. *Academy of Management Review 14(4)*, 532–550.

Forza, C., & Salvador, F. (2002). Managing for variety in the order acquisition and fulfilment process: The contribution of product configuration Systems. *International Journal of Production Economics 76(1)*, 87–98.

Halman, J.I.M., Hofer, A.P., & van Vuuren, W. (2003). Platform driven development of product families: Linking theory with practice. *Journal of Product Innovation Management 20(2)*, 149–162.

Hauser, J.R. (2001). Metrics thermostat. *Journal of Product Innovation Management 18(3)*, 134–153. ?3?

Henderson, R.M., & Clark, K.B. (1990). Architectural Innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly 35(1)*, 9–30.

Hobday, M. (1998). Product complexity, innovation and industrial organization. *Research Policy 26(6)*, 689–710.

Hobday, M., Rush, H., & Tidd, J. (2000). Innovation in complex products and systems. *Research Policy 29(7/8)*, 793–804.

Jiao, J., & Tseng, M. (2000). Understanding product family for mass customization by developing commonality indices. *Journal of Engineering Design 11(3)*, 225–243.

Kogut, B., & Kulatilaka, N. (1994). Options thinking and platform investments: investing in opportunity. *California Management Review 36(2)*, 52–71.

Krishnan, V., & Gupta, S. (2001). Appropriateness and impact of platform-based product development. *Management Science 47(1)*, 52–68. ?4?

Krishnan, V., & Ulrich, K.T. (2001). Product development decisions: A review of the literature. *Management Science 47(1)*, 1–21.

McGrath, M.E. (1995). *Product Strategy for High-Technology Companies*. Homewood IL: Irwin.

Meyer, M.H., & Lehnerd, A.P. (1997). *The Power of Product Platforms: Building Value and Cost Leadership*. New York: Free Press.

Meyer, M.H., & Utterback, J.M. (1993). The product family and the dynamics of core capability. *Sloan Management Review 34(3)*, 29–47. ?5?

Meyer, M.H., Tertzakian, P., & Utterback, J.M. (1997). Metrics for managing research and development in the context of the product family. *Management Science 43(1)*, 88–111.

Moore, W.L., Louviere, J.J., & Verma, R. (1999). Using conjoint analysis to help design product platforms. *Journal of Product Innovation Management 16(1)*, 27–39.

Pine, J.B. (1993). *Mass Customization: The New Frontier in Business Competition*. Boston: Harvard Business School Press.

Robertson, D., & Ulrich, K.T. (1998). Planning for product platforms. *Sloan Management Review 39(4)*, 19–31.

Salvador, F., Forza, C., & Rungtusanatham, M. (2002). Modularity, product variety, production volume, and component sourcing: Theorizing beyond generic prescriptions. *Journal of Operations Management 20(5)*, 549–575. ?6?

Sanchez, R. (1995). Strategic flexibility in product competition. *Strategic Management Journal 16*, 135–159. ?7?

Sanchez, R., & Mahoney, J.T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal 17*, 63–76.

Sanderson, S., & Uzumeri, M. (1995). Managing product families: The case of the Sony Walkman. *Research Policy 24(5)*, 761–782.

Sawhney, M.S. (1998). Leveraged high-variety strategies: From portfolio thinking to platform thinking. *Journal of the Academy of Management Science 26(1)*, 54–61.

Simon, H.A. (1969). *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

Soininen, T., Tiihonen, J., Männistö, T., & Sulonen, R. (1998). Towards a general ontology of configuration. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 12(4)*, 357–372.

Svensson, C., & Barfod, A. (2002). Limits and opportunities in mass customization for "build to order" SMEs. *Computers in Industry 49(1)*, 77–89.

Tseng, M.M., & Jiao, J. (1998). Fundamental issues regarding developing product family architecture for mass customization. *5th Int. Conf.*

Industrial Engineering and Engineering Management, Beijing, August 1998.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy 24(3)*, 419–440.

Utterback, J. (1994). *Mastering the Dynamics of Innovation*. Boston: Harvard Business School Press,

Wheelwright, S.C., & Clark, K.B. (1992). *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*. New York: Free Press.

Yin, R.K. (1994). *Case Study Research: Design and Methods*. Thousand Oaks, CA: Sage.

Yu, J.S., Gonzalez–Zugasti, J.P., & Otto, K.N. (1998). Product architecture definition based on customer demands. *ASME Design for Manufacturing Conference*, DETC98/DFM-5679, Atlanta, GA.

Adrian P. Hofer is a Researcher and Consultant specializing in product family management. He graduated from the Swiss Federal Institute of Technology with a BS in industrial management and manufacturing engineering and earned a PhD in business administration from the Institute of Technology Management at the University of St. Gallen, Switzerland. His interests are new concepts for product family management and their application in industry. Dr. Hofer is currently conducting a joint research project on a valuation model for product platforms in cooperation with Eindhoven University of Technology.

Johannes I.M. Halman is Professor of Innovation Processes at the University of Twente and Associate Professor of Innovation Management at Eindhoven University of Technology. He earned an MS in construction engineering from Delft University of Technology, an MBA (cum laude) from Rotterdam School of Management at Erasmus University, and a PhD in Technology Management from Eindhoven University of Technology. Dr. Halman's research interests are in the field of innovation management, with a primary focus on program and project management of innovation processes, new product platform development, risk management, and high tech start-ups.