IMPROVING CROSS-FUNCTIONAL COMMUNICATION ABOUT PRODUCT ARCHITECTURE

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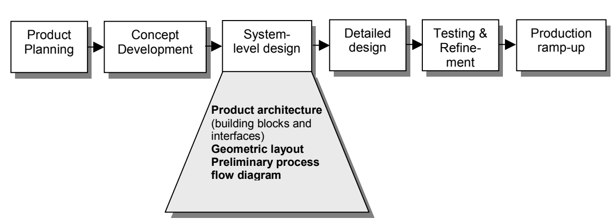
Product architecture decisions, such as product modularity, component commonality, and design re-use, are important for balancing costs, responsiveness, quality, and other important business objectives. Firms are challenged with complex tradeoffs between competing design priorities, face the need to facilitate communication between functional silos, and to learn from past experiences. In this paper we present a qualitative approach for systematically evaluating the product architecture of an existing product or product family, linking the original architecture objectives and actual experiences.
The intended contribution of our research is threefold: (1) to present a framework that brings together a diverse set of product architecture-related decisions and a set of business performance elements; (2) to provide a set of metrics that operationalize the variables in the framework, and (3) to provide a workshop protocol based on the framework and the metrics that improves cross-functional communication about the product architecture of an existing product family and results in practical improvement actions for future architecture design projects. Experiences with this approach are reported in pilots with Philips Domestic Appliances & Personal Care, and Philips Consumer Electronics.

1. Introduction

There is growing attention for product architecture decisions and the effects of these decisions on business functions such as marketing, supply chain management, production, and cost management (Mikkola, 2003). A product architecture is a translation of functional requirements into a physical definition of building blocks. More completely, it can be defined as: the functional decomposition of a product into subsystems, components, and parts, and the complete specification of the interfaces between these subsystems, components and parts describing how these interact within the product (Sanchez, 1998). Product architecture decisions are typically made during what Ulrich and Eppinger (2000) called 'the system-level design phase' of a product creation process, see Figure



1.

Figure 1. Product architecture decisions within the product development process

Product architecture decisions do not only affect costs (such as development costs, product costs, service and other after-sales costs), but these also—and sometimes more importantly—provide or hamper opportunities to leverage current product technology and functionality into new products and markets (Meyer and Dalal, 2002). Given this longer term impact, product architecture decisions are particularly relevant at the level of a group of products rather than for individual products. This is also referred to as "product platforms" to indicate that significant architecture decisions are made for a product family (Ulrich, 1995).

The product architecture concept is applied in a variety of industries. For example, the automotive industry is known for its deliberate policies to create product architectures that allow a range of models to be build from a common platform (MacDuffie et al. (1996), such as the Volkswagen company (Dahmus et al., 2001) and various Japanese companies (Muffato (1999a), Muffatto (1999b)). Another example is the printer and copier business, where companies have created product architectures that allow a wide range of end products to be assembled from a relatively small number of core printing/copying units that are combined with modules for specific functionalities related to handling originals, paper, and copies (Lee, 1996). The product architecture concept also plays an important role in the consumer electronics industry. The Sony Walkman is a well-known example in this respect (Sanderson and Uzumeri, 1997). Sony developed 200 models based on only half a dozen tape transport mechanisms and introduced these models into virtually every niche. It even introduced products that created niches and successfully pre-empted, through frequent model changes and scrupulously timed product innovations, competitors with equivalent resources and technical competence. Another example from the consumer electronics industry is Black & Decker, which completed a common and robust product platform for electromechanically powered tools in which motors, bearings, switches, gears, cord sets and fasteners were standardized. The company introduced from this platform a multitude of derivative products while at the same time reducing labor, insulation and operating costs up to 85% (Meyer and Lehnerd, 1997). The case company in this paper, Philips, also successfully applies the product architecture concept. The company developed, for example, a platform for electric toothbrushes using a set of common core components from which more than 300 significant product variations could be readily configured (Sanchez, 2004).

Product architecture decisions are complex, because of the many consequences and the lack of data and models that can provide estimates of these consequences in a specific context. On the one hand, these are of a *strategic* nature since they can shape the functionality of a whole product family and impact a product's market potential (see for example Sanchez, (1998), Clark and Wheelwright (1993), McGrath (2001)). On the other hand, these decisions can have far-reaching *operational* consequences that are felt across various functions in the organization and beyond in relationships with suppliers (Mikkola, 2003). Often, these downstream activities impose restrictions on the architecture decisions that may be costly to remove. Thus, a complex trade-off has to be made between strategic design objectives and downstream constraints (Lin and Chen, 2002). Unfortunately, data and models that can provide estimates of the consequences of an architecture design choice in a specific context are mostly lacking.

Previous research in the area of product architecture has particularly provided design approaches for developing and implementing product architecture policies. These approaches often focus on one specific architecture decision, such as modularity, commonality, or re-use of components. See, for example, Baldwin and Clark (2000), Dahmus et al. (2001), Fisher et al. (1999), Fujita (2002), Gonzalez-Zagusti et al. (2000), Marshall and Leaney (2002), Martin (1999), Meyer and Dalal (2002), Ramdas and Sawhney (2001), Robertson and Ulrich (1998), Sudjinato and Otto (2001) and Ulrich and Eppinger (2000). Gershenson et al. (2004) present an overview of research on measures of product modularity and methods to achieve modularity in product design. Kuo et al. (2001) review literature on design for manufacturing and design for 'X' more broadly (such as design for assembly, quality, recycle ability & environment, quality & reliability, and maintainability. Nayak et al. (2002) present the Variation-Based Platform Design Method (VBPDM) for product family design, which aims to satisfy a range of performance requirements using the smallest variation of the product designs in the family. Jiao and Tseng (2000) developed commonality indices that enable analytical measurement of product family characteristics, thus presenting a pre-requisite for understanding the relationships between product family structures and performance.

In contrast with the abundant literature on architecture development, not much research attention seems to be paid to the evaluation of the architecture decisions regarding their consequences on the (financial) performance of downstream activities. The focus is mainly set on individual products, such as why products are successes or failures, rather than product platforms (Meyer and Dalal, 2002). Some studies developed efficiency and effectiveness metrics, which describe the amount of time and costs (e.g., development, engineering) for derivative products compared to the initial product platform (see for example Meyer and Lehnerd (1997), Meyer and Dalal (2002), Meyer et al. (1997)). In order to make profound architecture decisions for future generations, there is a need for additional insights in the linkages between the architecture decisions and their impact on business performance.

In this paper we discuss a product architecture evaluation approach that is complementary to existing methods, being different in that (1) several aspects of product architectures and their potential impact on business performance aspects are presented in a coherent framework; (2) the variables in this framework are operationalized into a set of metrics that can be used to quantify the current state of a specific product architecture; and (3) the evaluation approach is about systematically exchanging information about existing product architectures from various perspectives and experiences in the organization. Systematically here means: an approach for structuring the communication, rather than a formally defined design approach. The application of the product architecture concept requires that various disciplines such as Engineering, Design, and Marketing work together in teams and coordinate their efforts. This implies that more integration issues need to be addressed during new product development (Kuo et al., 2001). Notions such as integration, learning, and functional cooperation are the background of the approach presented here, and as such our approach complements the existing quantitative design methods that focus on specific decisions.

This paper is based on empirical work with Philips' Center for Industrial Technology. This center supports product divisions of Philips and high-tech companies outside Philips in areas such as technological innovation, industrial technology and equipment, product innovation, and business and strategic topics. The approach was developed based on discussions with experts who could draw on their experience in product architecture development projects, which provided both content to the approach (what should be in the framework, how can it be measured) as well ideas about how the approach might be used in a real setting. Next, the approach was tested at two sites of Philips. These test sites provided feedback on the practical usability of the framework as well as the metrics.

The remainder of this paper is structured as follows. We will discus the evaluation approach and the literature on which it is based in section 2. Results of two pilot studies are reported in section 3, and section 4 concludes the paper.

2 The Product Architecture Evaluation Approach

2.1 Introduction

The product architecture evaluation approach is a structured method to discuss an existing product architecture and its impact on the business performance, to learn from it, and to give recommendations towards future product architectures. The approach consists of a questionnaire and a workshop, which should be attended by representatives from several disciplines who are or were somehow involved in the creation and management of the product architecture, for example: product architects, marketing representatives, cost engineers, purchasing-, production- and supply chain managers. Integration, mutual learning, and functional cooperation are then possible.

In the approach, the 'relation matrices' framework plays an important role. The framework, which is presented in Figure 2, is intended to clarify how product architecture decisions are linked to performance at business unit level via the intermediate concepts of product architecture capabilities, and performance at organizational level. The matrices are not exhaustive, but bring together relevant issues from different business functions. They are based on an extensive literature review, as will be described in more detail in the next sections. The variables in the matrices are described in the main text; specific metrics that have been used as their operationalization in the questionnaire are listed in Appendix 1.

Perf. at org. level	Sales	Cost of Goods & Sales	Working Captial (stock)	Investment
Quality	+			
Delivery	+			
Cycle Time	+	+		
Waste	+	+	+	+

Perf. at org. level	Leverageability	Alignment	Robustn.& Adapt.	External Development	Technical Performance
Quality	+	+		+	+
Delivery		+			
Cycle Time	+	+	+	+	+
Waste		+			

Product architecture decisions	Leverageability	Alignment	Robustn.& Adapt.	External Development	Technical Performance
Re-use		+			+
Commonality	-	+			+
Modularity	+	+		+	+
Anticip. Means			+		
Integrality	-	+			-

(Column group headings: Perf. at business unit level; Product architecture capabilities)

2.2 Product architecture decisions

The notion of a product architecture as the translation of functional requirements into a physical definition of building blocks is something that applies to many different kinds of industries. The product architecture decisions are choices with respect to re-use, commonality, modularity, integrality and 'anticipation means'. These decisions affect the *physical composition* of the product. In order to illustrate the characteristics, the product architecture of the Philips' electric 'Sensiflex' toothbrushes will be used here, see Figure 3.

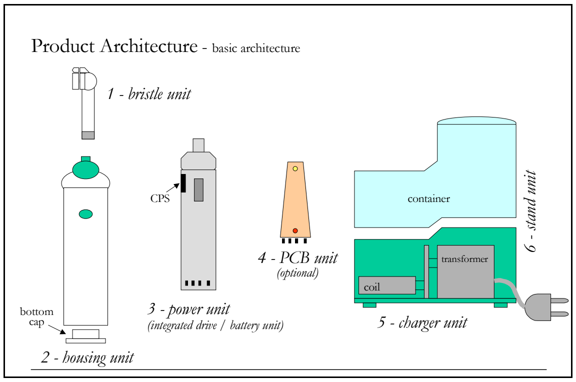


Figure 3. Product architecture electric toothbrush example

Re-use

Re-use is the decision to re-use part of the product architecture in a subsequent product generation (Sanchez and Sudharshan (1993), Sanderson (1991)). Re-use works backward and forward. First, re-use takes place when attributes from a previous generation are brought over to the present generation of the product architecture. Secondly, re-use can take place when attributes are planned to be used in future generations of the product architecture. In essence re-use contributes to the standardization of the product architecture over several generations. Three levels of re-use can be distinguished: 1) re-use on solution level, 2) re-use on design level (ready for copy-paste), and 3) re-use on physical level (for example building blocks and interfaces) (Corso et al., 1999). Application of re-use may result in improved efficiency, lower risks and faster time-to-market. Re-use on product level will enable re-use in production equipment, resulting in further efficiency and economy of scale benefits.

In the toothbrush example (see Figure 3), the bristle unit and the interface between bristle unit and the power unit were re-used: it is taken over from a previous generation to maintain compatibility with replacement brushes. Further it was judged that the interface would not restrict foreseen innovations in these units during the lifecycle of the 'Sunshine' products. The bristle unit itself was re-used, since it still met the functional and performance requirements. No building blocks or interfaces are defined to be re-used in a future architecture, but also not excluded to use in a future generation.

Commonality

Commonality is the decision to use attributes across product variants in a product range (Bremmer (1999), Fisher et al. (1999), Sanchez and Sudharshan (1993), Ulrich and Eppinger (2002)), for example covering one product family. Commonality contributes to the standardization of product architectures. Commonality in building blocks for a specific product range also requires interface definition or standardization for this range. Commonality in product variants can be realized at several levels of abstraction, which are: specification, physical principle, solution, technology, building blocks, parts and modules. Commonality on product level (just as re-use) enables commonality in production equipment. In the 'Sunshine' toothbrush, the charger unit was common for all product variants in the product range; see Figure 4 for a picture of the charger unit.

Figure 4. Charger unit, toothbrush example

Modularity and Integrality

A key distinction can be made between integral and modular product architectures (Ulrich and Eppinger (2000), Ulrich (1995)). An integral architecture means that many different functions are fulfilled by one physical unit of the product, while a modular architecture means that one physical unit fulfils one (or a limited set of complete) function(s). The ideal is that it is possible to exchange one module for another with different characteristics (cost, quality, or functionality) without having to make any changes in other modules or parts of the product. This requires design characteristics such as standardized interfaces between modules and modules that are separately testable (Tsai and Wang, 2003) and configurable, and that, for example, can be developed by suppliers (rather than individual parts) (Mikkola (2003), Sanchez and Sudharshan (1993)). Modularized products facilitate product differentiation to meet the market requirements now and in the future (Muffatto and Roveda (2000), Ulrich (1995), Ulrich and Eppinger (2000), Sanchez and Collins (2001)). Modularity also aims at separately testable building blocks (Tsai and Wang, 2003).

In the 'Sunshine' toothbrush, the housing unit and the PCB unit are modular building blocks and, hence, require standardized interfaces. These building blocks are defined such that easy substitutability to offer product differentiation is possible; see Figure 5.

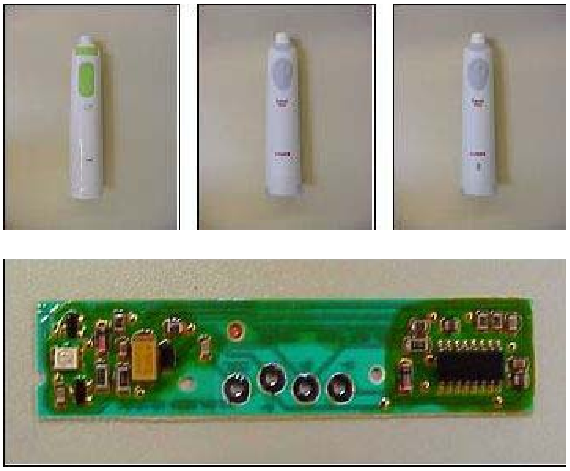


Figure 5. Housing unit and printed circuit board

Integrality is more or less the opposite of modularity: the decision to combine multiple functions on one building block, consciously accepting the high internal physical and functional coupling resulting from this integration. In the 'Sunshine' case for example, the power unit is an integral building block. Here, the battery, motion converter, motor, switch, and charging functions are mapped on one building block. See Figure 6 for a picture of the power unit.

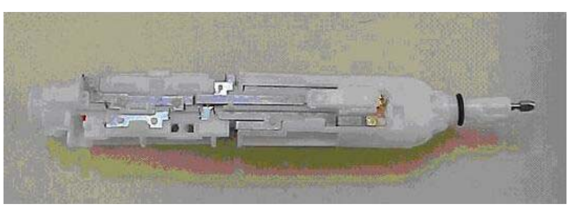


Figure 6. Power unit

Anticipation means

Anticipation means are consciously built-in solutions in a product architecture to anticipate on foreseen changes and 'known unknown' uncertainties in the future. Sanchez and Heene (2004) describe 'known unknown' uncertainty as a form of ignorance when decision-makers are aware of a factor that could affect a situation, but do not know how to assess or handle the possible impact of that factor on the situation. The anticipation can take place in the following areas: available technologies in the future, ways how components are realized in the future, shifts in the business model, changes in the industrial setting, changes in an organization's strategic outsourcing policy, changes in specific standards & regulations, changes in external development opportunities and efficiency & effectiveness improvements programs. These areas of uncertainties or foreseen changes are recognized by, for example, Clark and Wheelwright (1993), Porter (1980), and Robertson and Ulrich (1998). Anticipation to these uncertainties could be done through, for example, configurability (building blocks can be added or removed), scalability (the functionality of a common building block can be turned on or off or its parameters can be tuned) or separation (a specific function is deliberately assigned to a separate building block). The aim of these 'anticipation means' is to keep certain options open (not to exclude them in advance) or to prevent significantly risky, costly and time-consuming modifications once adaptations are necessary in the future.

2.3 Product-architecture capabilities

Product-architecture capabilities describe the *goals* that the product architecture should realize by the right 'product architecture decisions' as discussed in the previous section. In other words, the 'product architecture capabilities' show what the product architecture is actually capable of. These capabilities are discerned into: technical performance, leveragability, alignment, adaptability & robustness, and external development opportunities.

Technical performance

Technical performance is probably the most dominant and initial objective that should be realized by the product architecture. The product architecture should enable the correct technical functioning of the product variants in the first place. If this is not achieved, all other architecture objectives do not make any sense. It is not the objective of this paper to cover aspects that characterize the technical functioning and performance, because formal assessment methods and tools for this purpose already exist.

Leveragability

Leveragability is the ability to efficiently and effectively develop and create product variants from a set of building blocks and standardized interfaces that are compliant with a defined reference architecture (Meyer and Lehnerd (1997), Sanchez (1996), Martin (1999), Sudjianto and Otto (2001). It needs to be stressed that leveragability deals with the *planned* number of product variants that might be actually developed and marketed over the lifecycle of the product architecture, some of which are initially developed, and other product variants are developed after the initial range is introduced in the market.

Alignment

In essence, alignment means that the product architecture will be defined in line with the requirements or capabilities of the production system and the supply chain (including the supply base). The product architecture that needs to be defined can take these requirements into consideration and incorporate them, which leads to substantial benefits ('Fachbericht Productentwicklung' (2003), Bremmer (1999), Tatikonda (1999)). The alignment between the product architecture and the production system covers the aspects of a common product structure, a common production flow, a common production structure, common interfaces between product and production means, the number and testability of subassemblies and the proliferation of product diversity throughout production. The elements that describe the alignment between the product architecture and the supply chain and supply base characteristics can be discerned into: number of building blocks (including variants per building block), number of product variants, match of diversity profile with the customer order de-coupling point (CODP) and the match between the building block characteristics with the supplier capabilities (Baiman et al. (2001), Krishnan and Ulrich (2001), Lee (1996), Lee and Tang (1997), Kusiak (2002)).

Adaptability & Robustness

Product architectures are defined for a specific time frame, not for just the moment. When considering the future, changes can occur and uncertainties can show up in various forms and to different extents as mentioned before. Robustness describes the desired ability to adjust the product architecture to the foreseen changes and 'known unknown' uncertainties in the future. The way these adjustments are actually realized is called adaptability. Adaptability describes the desired ability to adjust the product architecture or its building blocks (in case this purpose has been decided for) in a fast, low cost and low risk manner. These adjustments should be made without considerable modifications in the product architecture. Hereby can be thought of: adjustments that do not have an impact on the interfaces of the product architecture, and the deployment of solutions based on 'anticipation means' decisions in the product architecture to adjust the product to this foreseen change or uncertainty.

External development opportunities

Sometimes other parties have superior competencies in developing the physical realization of required product functionalities. To be able to work effectively with other parties, conscious decisions need to be made which parts of the product architecture will be further detailed in-house and which will be developed externally (Ulrich and Ellison, 1999). The product architecture can be defined such that suitable functions are separated (de-coupled) from the other parts of the architecture and that interfaces are well defined, making it actually possible to use these external development capabilities in an efficient way (Mikkola (2003), Sanchez and Sudharshan (1993)). External development can be discerned into 1) co-operation with other organization(s), 2) fully outsourcing to another organization, or 3) purchasing and applying of available standard building blocks.

Within the 'Sunshine' project, a standard motor is used in the power unit and next to this the development of the complete charger is outsourced.

2.4 Performance at organizational level

The 'product architecture capabilities' measurably affect the performance of departments such as Marketing, Production, Supply Chain Management and Development. Lynch and Cross (1991) explicitly make a distinction between external and internal performance. From an external point of view, the customers determine what is important to measure: quality and delivery. From an internal perspective, the own organization determines what is important to measure, being cycle time and waste.

Quality

Quality can be described in many ways and there is even no straightforward all-embracing proper definition of quality. Quality deals with: features, performance, durability, reliability, aesthetics, perceived quality, and the extent to which the product satisfies customer requirements (Lynch and Cross (1991), Clark and Fujimoto (1991), Clark and Wheelwright (1993), Fisher et al. (1999)).

Delivery

Delivery is defined as the quantity of the product or service delivered on time to the customer, as requested by the customer (Lynch and Cross, 1991). The underlying elements of 'delivery' are discerned into: supply chain reliability, volume flexibility and mix flexibility. Reliability in the supply chain addresses the extent to which customer orders are realized.

Cycle time

Cycle time represents all time-related activities of an organization's departments. Lynch and Cross' (1991) cycle time concept covers both horizontal and vertical time. The horizontal time represents the time span between two points, for example: time to market (Griffin (1993), Griffin (1997), Graves (1989)), customer order lead-time, supply cycle time, throughput cycle time or time to quality. The vertical time represents the required efforts to get things realized. This can be measured by, for example, the development effort (Meyer et al., 1997) or the (in)direct labor content.

Waste

Waste is described as all non-value adding activities and resources that are incurred in eventually meeting the customers' requirements (Lynch & Cross, 1991). In this article the following concepts are used to measure the existence of waste: the degree in which economies of scale are realized (for example: utilization of machine and tools capacity, life cycle of equipment and tools and bill of material), the degree of efficiency (for example, average machine utilization) and the amount of inventories (for example, inbound inventory, work-in-progress inventory, and end product & commercial inventory).

2.5 Performance at business unit level

The ultimate goal of developing, manufacturing and selling products is, of course, to realize a certain profit. This paragraph turns the 'performance at organizational level' into financial measures and discusses the last part of the relation matrices. The 'performance at organizational level' can be discerned into: sales, cost of goods sold, working capital and investment. Also here, a distinction is made in performance from both external and internal perspective. 'Sales' represents the external perspective and 'cost of goods & sales', 'working capital' and 'investment' represent the internal perspective. These four ingredients are used within Philips' accounting method to calculate the overall profitability. This method is derived from the classic Dupont scheme.

- In the accounting framework, sales are only represented by the turnover for all product variants that are part of a range over the lifecycle. However, in order to represent the external performance at business unit level more completely, some additional indicators are added, such as sales volumes, average selling price, relative price setting, sales impact, success rate and market share (Griffin (1997), Cooper and Kleinschmidt (1995), Sanchez and Sudharshan (1993)).
- The cost of goods & sales are determined by the material, machine, development, direct and indirect labor, marketing, sales, service and depreciation costs.
- Working capital is normally defined as: inventory, plus accounts receivable, plus cash needed for normal operations, minus non-interest bearing accounts payable. Product architecture decisions primarily impact the inventory value, hence only this element is included.
- Investments particularly represent the product specific investments in equipment, tools and supporting systems (Sanderson (1991), Robertson and Ulrich (1998)). Non-specific company wide or factory related fixed assets are not considered here, because these are not influenced by the product architecture decisions.

2.6 Applying the product architecture evaluation approach

The 'relation matrices' framework described in sections 2.2 through 2.5 above forms the basis of our product architecture evaluation approach. The primary objective of this evaluation approach, is to facilitate communication and exchange of knowledge among the relevant business functions. It consists of a questionnaire and a workshop.

The questionnaire has to be completed by the workshop participants in advance of the workshop. It is used to (1) stimulate workshop participants to think in advance about the product architecture and its impact on the business and (2) gather information that is used during the workshop to start the discussion. The questionnaire contains questions that address the operationalizations (metrics) of the concepts in the relation matrices (see Appendix 1).

The purpose of the workshop is to provide a structured learning experience regarding product architecture implications, and to generate recommendations about future product architecture decisions for similar products. In the workshop, which is suggested to be prepared and executed according to the protocol presented in Appendix 2, the discussion is stimulated and structured through the questionnaire results and the relation matrices. The intention of the workshop is to discuss, for the product group under consideration, which relationships between the concepts in Figure 2 were most prominent, why this is so, and how this is related to decisions made during product development. The 'plus' and 'minus' symbols in Figure 2 are suggestions for such relationships, based on the literature. However, as discussed in our introduction, to our knowledge the relationships between product architecture decisions and business performances have not yet been studied in such an integrated way. Hence the set of relationships show in Figure 2 is probably not complete. Furthermore, not all of the presented relationships have been empirically validated and some may only apply under specific conditions. Thus, the plusses and minuses should only be used as a starting point for discussion, and the workshop participants should discuss the specific relationships in their own case, focussing on:

- intended relationships that turned out to be successful, which can lead to some good practices to be maintained for future projects;
- intended links that turned out to be unsuccessful, which can lead to recommendations what to do differently next time;
- unintended or unforeseen links, and in case of missed opportunities, recommendations can be made how to consciously deal with these links;
- relationships between product architecture and its impact on the performance at organizational and business-unit level, which can lead to concrete ideas for better serving business goals in future projects.

3 Testing of the product architecture evaluation approach

3.1 Test criteria

In this section, we will describe results of two empirical pilot-tests in which the 'usable' of our approach for exploring product architectures and their impact on the performance at organizational and business unit level have been evaluated. The term 'usable' can be divided into scientific usability and practical usability (Yin, 1995). Scientific usability can be further split into reliability and validity. Reliability can be achieved through standardization and objectivity (Leyten and Hufen, 1987). The protocol presented in Appendix 2 as well as the fact that a multi-functional group of participants guided by a facilitator perform the assessment, are expected to contribute to the reliability of the results. Validity can be split into three aspects (Geurts, 1999):

- Notion validity: are concepts correctly operationalized? Most of the notions used in our approach have been adopted from literature and tested by other researchers. We assume that these are valid. In the two test cases at Philips, we have also tested whether the concepts were rightly understood by the participants.
- Internal validity: are the assumed causal relationships valid? In our approach we hypothesize that discussing the relation matrices will result in learning and identification of improvement opportunities for future architecture designs. Whether this is true will have to be tested through repetitive use in practice.
- External validity: to what domain can the conclusions be generalized? Also, this generalizability of the approach will have to be tested more broadly in practice.

Practical usability refers to applicability in real-world situations. This requires 'acceptation' and an 'integral character'. In order to be accepted, the approach and the terminology used will have to be comprehensible for the participants and the results will have to be perceived as relevant and convincing (Van Ekert, 1995). Furthermore, the approach should be integral, meaning that there are neither main gaps nor a lot of redundancy, and that the approach should not result in an overload of information (Geurts, 1999). In an evaluation of the product architecture evaluation approach at two sites of Philips, we have mainly focused on these practical usability aspects.

3.2 Test-cases

The product architecture evaluation approach was tested in two cases. The first case concerned Philips Domestic Appliances and Personal Care (DAP) in Klagenfurt, Austria. At this site an architecture competence team (ACT) is set up, consisting of employees from several functional disciplines, such as: development, production, supply chain, F&A and purchasing. By being involved in all architecture activities in Klagenfurt, ACT members are systematically improving their knowledge of key issues and good practices in the architectural creation process. The first author of this paper visited the site and worked with two members of this ACT. The product architecture of the 'Sunshine' project, which is used as an example throughout this article, was the focus of the product architecture evaluation approach.

The second case concerned Philips Consumer Electronics (CE), business unit multimedia displays. A development team consisting of several architects is responsible for the development of new products and architectures. The general R&D manager for monitors was the participant for the pilot case, through video conferencing. The product architecture called 'Hudson' is used during the pilot-case. The obtained data about the product architecture are highly confidential and no authorization for publication was given.

3.3 Results

Questionnaire

The overall impression of the questionnaire was that it fulfilled the usability requirements of comprehensibility, relevancy, and completeness. The questionnaire was evaluated on five criteria: are the questions understandable, are definitions clear, are data available, are the formats for answering the questions suitable, and are the questions relevant? In the pilot-case at Philips DAP, 53 of the 58 questions were discussed, and in the pilot-case at Philips CE, 21 out of the 58 questions were discussed (because less time was available). The score on the criteria are presented as a percentage of the discussed questions, and results in Figure 7 show that 85 and 100 percent of the questions could be answered. According to the participants, the definitions used are consistent and complete, and the questions were mostly understandable, relevant, and presented in a logical way. Hence, they did not suggest changes, additions, or removal of questions. According to their judgement the questionnaire was balanced and no concepts were over- or under emphasized.

During both pilot-cases the participants mentioned that some questions (e.g., number of code numbers, initial range versus derivative range) triggered them to focus more on particular product architecture decisions in future generations. It was mentioned that the questionnaire could also be used as a checklist during the architecture creation process. The workload of the questionnaire was estimated to be one day, mainly because much information had to be gathered from various sources and was mostly not directly available. Based on the participants' comments, it can be concluded that despite the relatively high workload the questionnaire was worth it.

Philips DAP (53 out of 58 questions discussed)

	Met criteria	Percentage
Question understandable?	51	96%
Definitions clear?	48	91%
Data to answer available?	51	96%
Answer in current format?	46	87%
Question relevant?	53	100%

Philips CE (21 out of 58 questions discussed)

	Met criteria	Percentage
Question understandable?	20	95%
Definitions clear?	19	90%
Data to answer available?	21	100%
Answer in current format?	21	100%
Question relevant?	21	100%

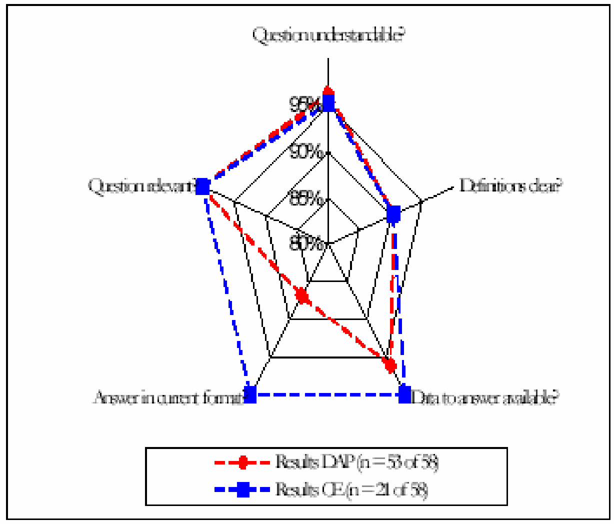


Figure 7. Evaluation of questionnaire items

Workshop

During the CE pilot case, the first author of this paper presented the relation matrices and their characteristics to the general manager of R&D for monitors. The manager took the 'Hudson' architecture as an example and responded that especially commonality and modularity were important. Commonality positively influenced alignment with the production process and modularity particularly enabled external development. Alignment resulted in lower inventories and external development resulted in improved product quality.

During the DAP pilot-case, the workshop was executed according to the protocol in a condensed form: only one matrix was extensively discussed, the others were only evaluated on a high level. The 'Sunshine' product architecture was the focus of this case study. Just as in the Hudson project, the participants in the Sunshine project recognized links in the relation matrices. They indicated that, for example, the modular housing unit contributed to a great extent to leveragability, enabling easy development of product variants and even customer specific variants. Eventually, these quality aspects positively influenced sales.

Since the participants both pilot cases were quite able to apply the content of the relation matrices to their architecture, it can be concluded that characteristics and structure of the relation matrices seemed to be clear. Even without elaboration, it was obvious to them that the cells represent links between variables and by linking all matrices 'architecture decisions' could eventually be brought in relation with 'performance at business unit level'. No suggestions were made with respect to adding or removing concepts. For now, the relevant issues seem to be included. However, it is not negligible that in some businesses other characteristics or underlying elements are relevant.

No questions were raised about the objective of the workshop. It was clear that the purpose was to give recommendations towards future product architectures by discussion of a particular product architecture with representatives from different functional disciplines.

The "introduction document" (see step 1 in Appendix 2) was also evaluated. The general impression was that it was a difficult document to read, due to the large number of concepts introduced. This document was, however, seen as vital for the workshop, because it provided an extensive overview of the relation matrices and the concepts used, so that participants could start the workshop with the same level of knowledge. This document in combination with the results of the questionnaire made the topics more understandable.

In both cases, we conclude on the basis of the participants' reactions, that the value of the questionnaire and workshop were acknowledged. The perceived value of the workshop may be explained on several grounds. First, the relation matrices contributed to the awareness that decisions with respect to architecture creation have impact on the performance at organizational and business unit level. The 'conservative' idea that product architectures are only developed in order to serve technical purposes is challenged. It was shown how conscious architectural thinking and decision-making can positively contribute to performance at both organizational and business unit level. Secondly, the workshop pursued an integral and multi-disciplinary approach in assessing a particular product architecture. Several functional disciplines that were involved during development or management of the product architecture considered from their individual perspective how it performed. This multi-functionality led to insights that contributed to the team's knowledge and experience and provided specific recommendations towards future product generations. Thirdly, in line with the previous, the workshop participants realized that the relation matrices could also be used as checklists when developing a follow up or new product architecture generation.

4 Conclusions and further research

Product-architecture decisions have a significant impact on an organization's ability to implement its strategy, because these decisions impact the speed and cost by which a firm can introduce new products, and the potential quality and functionality of these products. Studies in the literature have investigated many tradeoffs involved in product architecture decisions, and models for such tradeoffs have been developed. Also, successful applications of deliberate product architectures are reported in the literature. In this paper, we have discussed an approach for evaluating the product architecture of a firm's current products, in order to draw lessons for new products that the firm will develop. The approach is qualitative in the sense that it is about stimulating and organizing the exchange of knowledge, data, experiences from various functional silos and management levels in the organization in a workshop setting and through a preparatory questionnaire.

The approach considers various aspects that are related to product architecture, and this is a contribution to the literature, where evaluation approaches are usually focussed on more rigorous evaluations of one single product-architecture related topic. The framework is summarized in Figure 2. Drawing on various NPD literatures, we discussed five product-architecture decisions that determine the physical composition of products: re-use, commonality, modularity, integrality, and anticipation means. These decisions create (or limit) various possibilities for introducing new products. Further we discussed product architecture capabilities: leveragability, alignment, adaptability, external development, and technical performance. All these concepts have been operationalized in a questionnaire. Then we linked these capabilities to performance, at two levels: performance at the organization department level (quality, delivery, cycle time, and waste), and business-level performance (sales, cost of goods sold, working capital, investment).

Through its broad scope and qualitative method, the approach aims to stimulate and structure inter-functional communication about product-architecture decisions. Because these decisions have an impact on "everything" in the organization, there are likely to be ample improvement opportunities in many organizations if the information can be brought together: what are the experiences of Purchasing, Production, Distribution, Service, etc. and how can we use such evaluations for improving future product generations. In this context, the approach presented here aims to facilitate a process of systematically exchanging knowledge and experience, with two objectives: deriving concrete lessons learned for new generations of products, and creating an increased awareness of the inter-functional relationships resulting from product architecture decisions. The results of the small-scale tests in two pilot-projects at Philips that were briefly discussed in the paper supported the usefulness of the approach in that respect.

As any study, our study also had limitations, and the limited empirical testing of the approach needs to be mentioned here. Therefore, in the near future , testing of the approach in several case studies is planned. In these cases it is intended to apply the protocol from start to finish, followed by a structured evaluation with the participants. Nevertheless, we suggest that there is also value in conducting small-scale experiments such as the ones presented in this paper, which did take place in real organizations and were concerned with real products. The results of such tests can be used to modify the method before spending considerably more resources on future research. Furthermore, being able to present initial empirical results will facilitate getting access to larger-scale test sites.

Another topic for further research will be to empirically validate, for example in a large-scale survey, which links between the concepts in the relation matrices do generally or conditionally exist. More knowledge about such relationships would greatly enhance decision-making about the purposeful application of product architecture options. The questionnaire developed in our research could serve as a starting point for such a survey. However, given the amount of time currently required to fill out the questionnaire, further simplification and focus on the most interesting relationships will be needed to make it usable on a large-scale. The relationships identified in the planned test case studies as the strongest could be used as a starting point in this respect.

Appendix 1: Product architecture metrics

Characteristic from relation matrices	Metrics
None	Number of building blocks in product architecture Number of formally specified interfaces in product architecture
Re-use	Number of building blocks from previous product architecture generation Number of building blocks to be maintained in future product architecture generation Number of interfaces from previous product architecture generation Number of interfaces to be maintained in future product architecture generation
Commonality	Number of common building blocks in product architecture
Modularity	Number of functionally de-coupled building blocks in product architecture Number of separately testable building blocks in product architecture Number of 'plug and play' configurable building blocks in product architecture Number of modular building blocks in product architecture (check on previous metrics)
Anticipation means	Number of building blocks that anticipate on future uncertainties or foreseen changes Number of potential areas of future uncertainty or changes in which options are kept open in order to anticipate Number of built in solutions to anticipate on potential areas of future uncertainties or changes
Integrality	Number of integral building blocks in product architecture
Leveragability	Number of planned product variants over the product architecture's life cycle Number of planned product variants that will be initially developed
Alignment	Number of code numbers (excluding technical versions of building blocks) Number of code numbers (including technical versions of building block) Extent of common product structure (Commonality in the detailed physical execution and hierarchy of the product architecture, for example the hierarchy from parts, subsubassemblies and subassemblies) Extent of common production structure (Commonality in the structure for the implementation of: the required assembly and technology processes in a specific sequence and segmentation and additionally operations like testing, repair, buffering, sub-assembling and packaging) Extent of testable subassemblies Extent of common production technologies & processes Extent to which the product diversity is scattered over the production structure Location of product diversity in production process Extent of match between the building block characteristics and the supplier capabilities
Robustness & Adaptability	Number of utilized solutions to adjust the product architecture to uncertainties or foreseen changes Number of adjustments over the life cycle that have impact on the interfaces
External development opportunities	Number of external developed building blocks in product architecture Number of external developed interfaces in product architecture

Appendix 2: Workshop protocol

1) First, the workshop is prepared by a facilitator:
   - A document "Introduction to the workshop" is sent to the workshop participants a few weeks in advance of the workshop, describing the purpose, the protocol, and the relation matrices. This document enables the workshop participants to get acquainted with product architecture evaluation approach.
   - A questionnaire is sent to the workshop's participants also a few weeks in advance of the workshop. The questionnaire stimulates the workshop participants to think in advance about the product architecture and its impact on the performance at organizational and business unit level. After the questionnaire is completed by the respondents, the facilitator and each respondent go through it (e.g., discuss the answers, difficult questions and remaining obscurities).
   - The answers are summarized by the facilitator as input for the workshop.

2) The workshop is started with the following activities:
   - The facilitator presents the workshop's objectives and the interaction matrices, together with the questionnaire results, such that remaining obscurities about the relation matrices and their underlying characteristics become clear; an initial overall impression of the product architecture and its performance at organizational and business unit level is obtained; and the relation matrices become comprehensible in the 'language' of the workshop participants.

3) In the main part of the workshop, the facilitator and the workshop participants discuss the matrices:
   - The concepts of 'product architecture decisions', 'product architecture capabilities', 'performance at organizational level' and 'performance at business unit level' are judged on their relative importance, to assess which elements were emphasized during the architecture creation process.
   - An initial sifting of relevant links in the relation matrices is made, at the general level as presented in Figure 2 (for example, the link between 'modularity' and 'leveragability').
   - The relevant links are discussed in more detail, discussing the strength of the links between all concepts (e.g., –9 = strongly negative link, –3 = moderately negative link, +3 moderately positive link.).
   - In parallel, it is discussed why and how this product architecture performed as assessed in the questionnaire, and the do's and don'ts, advantages and disadvantages will be identified and analyzed. Then, recommendations towards future generations can be made.
   - The extent to which the product architecture impacted on the performance at organizational and business-unit levels is discussed.

4) The facilitator summarises the results of the workshop:
   - The facilitator calculates the sum of the characteristics' relative importance times the scores on a specific links (as is filled out in the relation matrices) to identify the dominant links.
   - The facilitator draws qualitative conclusions, summarizes the recommendations that are made during the discussion and gives own recommendations.

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