PROACTIVE MODELING OF MARKET, PRODUCT AND PRODUCTION ARCHITECTURES

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ABSTRACT
This paper presents an operational model that allows description of market, products and production architectures. The main feature of this model is the ability to describe both structural and functional aspect of architectures. The structural aspect is an answer to the question: What constitutes the architecture, e.g. standard designs, design units and interfaces? The functional aspect is an answer to the question: What is the behaviour or the architecture, what is it able to do, i.e. which products at which performance levels can be derived from the architecture? Among the most important benefits of this model is the explicit ability to describe what the architecture is prepared for, and what it is not prepared for - concerning development of future derivative products. The model has been applied in a large scale global product development project. Among the most important benefits is contribution to:

- Improved preparedness for future launches, e.g. user interface and improved energy efficiency
- Improved synchronization between product- and production development
- Achievement of attractive cost- and technical performance level on all products in the product family
- On time launch of the first generation of the product family

Keywords: product architecture, modeling product architecture, multi product development, production architecture.

1 INTRODUCTION
Many industrial companies are facing serious challenges in maintaining competitive advantages. Among the most often mentioned challenges are:

- There is a need to reduce time to market (and more importantly time to money) for new products and solutions. Some of the companies that have participated in this research have lost 25% of market share in certain business areas during the last year. The reason for this is, they do not have the right products available on the market.
- There is a need to achieve right cost level for global products– Immelt et al. [1] mention that for GE (General Electric) to be cost competitive, the company needs products that are 80% cheaper in China compared to US products.
- The need for localization and customization of products are increasing [2].

There are certainly many approaches to handle the above challenges, which are of organizational-, process-, tool-, and competence nature. The focus in this paper is architectures, i.e. design of product families or product programs based on stable interfaces and standard designs (modules). Implementing an architecture have relations to all of the above aspects, but the overall hypothesis of the research presented in this paper is that in order to improve the design of product families, architectures have to be modeled explicitly and visually.

Many kinds of research projects have been carried out in order to improve the understanding of architecture work. Among the most important contributions are [3], [4] and [5]. So why is there a need for further investigations? One answer is that nearly all definitions of architectures are of structural nature, i.e. what the architecture *is*. This is for obvious reasons very relevant, but equally important are the functional aspects of architecture, i.e. what the architecture able *to do*. For instance the ability to answer the question: Which products can be derived from the architecture? This phenomenon is not very widely understood and described. Furthermore, the links between market, product and production/supply architecture are relevant. This is also not in itself a new recognition, but when it comes to e.g. evaluating the consequence of adding or removing a feature in a product, it is very

difficult to model the consequences market- and production wise. It is the ambition to make a model that allows operational linking between the three architectures.
The reason proactive is mentioned in the paper title, is to address that there is a big business potential and necessity for companies to think ahead in product family design, meaning that the next 2, 3 or 4 launches of derivative products have to be taken into consideration explicitly. Architecture wise this means that an architecture shall be able to show the *preparedness* for the launching of future product generations.
The results presented in this paper is based on research in 3 PhD projects, Kvist [6], Harlou [7], and Pedersen [8] within modeling of architectures. The structure of the paper is as follows. Section two will report on some of the findings from observation of architecture work in main Scandinavian companies. Section 3 will identify the relevant modeling aspects to be included for modeling architectures. Section 4 will present state of the art concerning modeling of architectures. After that section 5 will describe a proposal for how to model market, product, and production architectures. In section 6 experience from application of the market, product and production architecture is explained.

2 WHY IS THERE A NEED TO IMPROVE ARCHITECTURE MODELING?

If a product assortment in a company is described by means of a traditional market matrix, it can be shown as below in Figure 1.

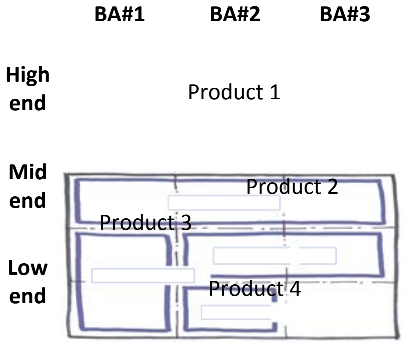

Figure 1. Product mix of a company:
The horizontal axis shows the Business Areas (BA) and the vertical axis describes the performance level of products ranging from low to high performance products

Because many products are designed without conscious decisions concerning the market coverage, poor product family design is carried out. Some of the bad decisions that we have observed in this research are:
One size fits all: In many companies the product architecture is shared from high end to low end products. One consequence of this is that low end products have too high costs and high end products are not sufficiently prepared for future launches. In some companies there is a conception that "stripping" the high end products is a way of developing low end products. There are perhaps examples where this can be done, but is in many cases not possible. In other words, "stripping a Rolls Royce does not bring a Volkswagen into existence".
Dedicated products – future generation products are not addressed: Product families are designed without sufficiently addressing facelifts and next generations. Some examples of this are variants developed on European development sites not prepared for UL approval. The consequence is that US product variants are significantly delayed. Another company is developing a dedicated product for hospitals. This product shall at a later stage also be used in large industrial laboratories. The consequence of developing a dedicated hospital product is a delay of the industrial product family by at least 1 year.
Spaghetti products: Some product families consist of subsystems with very complex interfaces and interactions. The consequence is that development of even small updates becomes very complicated and resource intensive.
Non value adding variety: There are many examples of variety in a product families that does not provide value to customers but only adds complexity cost. A few examples of this phenomenon are: One company is delivering products with actuators that are bolted, welded and glued. This means, that three types of production processes have to mastered, leading to increased cost. Seen from a customer point of view, this variety does not add value. Another company is having pressure tanks certified for

4.1, 4.4 and 5.0 bar. In this case certificates and approvals have to be developed and maintained without adding any extra value to the customers.
The consequences of the above issues are higher costs and reduced ability to launch new products. One of the means to handle the above issues is to develop product families based on explicit architectures. The next section will take a closer look on which phenomena to include in the modeling of architectures.

3 WHICH ELEMENTS SHOULD BE INCLUDED IN MODELING OF ARCHITECTURES

The paper is based on the so-called Product Family Master Plan Framework [7], [9], Theory of Technical Systems [10] and Theory of Domains [11]. Consequently three types of architectures are necessary, i.e. market, product and production/supply chain.

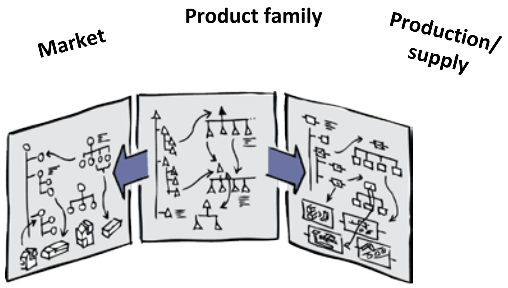

Figure 2. The Product Family Master Plan Framework

There exist many definitions of architectures in literature. Some of the most often quoted are:
"The combination of subsystems and interfaces defines the architecture of any single product. Every product has an architecture; the goal is to make that architecture common across many products", Meyer & Lehnard [5].
"An architecture is a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces to the surroundings", Harlou [7].
"In essence, a PFA (Product Family Architecture) means the underlying architecture of a firm's product platform, within which various product variants can be derived from basic product designs to satisfy a spectrum of customer needs related to various market niches", Jiao & Tseng [12].
All of the above definitions are underlying the importance of interfaces and description of how product families can be described. This is certainly very important, but the above definition is missing the clear distinction between structural and functional aspects of an architecture. Furthermore it does not explain the type of elements that are relevant in the structural and functional definitions. In accordance with Theory of Technical Systems [10] this research will reserve the word structure to how individual products are built up and architecture will be reserved for describing how a product family is built up including the future derivative products.
The next sub sections will explain some of the necessary architecture modeling requirements in market, product and production architectures that this research have identified.

3.1 Market architecture requirements

The overall purpose of the market architecture is to model what the product family shall cover and what it shall not cover. Often this is unclear leading to unfocused product architecture design.
Product properties across the product program: Taking a starting point in properties being obligatory, expected or positioning in the market place, properties can be realized by implementing them as either e.g. basic properties, differentiators or delighters in the product design – depending on the level of fulfillment.
Requirements across individual and all application areas: This is relevant in order to scope the product families, e.g. which areas shall be covered and which shall not be covered. Similarity and differences across application areas is in principle going to drive variety of the elements constituting the product architecture and flexibility of the production architecture.

Product family architecture definitions: This dimension is explaining which product families that shall be developed and how they cover the market grid as previously shown in e.g. Figure 1.
List of features and options: This is an important area since it is often difficult for projects to clarify how many features shall be implemented in high end, medium and low end products. It is also relevant to explicitly specify which features shall be implemented and which ones shall be postponed to later launches or simply omitted from certain market segments.
List of commercial variants that shall be launched to the market: This describes the complete list of individual products and which standard designs and features that goes into each product.

3.2 Product architecture requirements

The overall purpose of the product architecture is to describe the building principles for a product family.
List of structural elements: According to [7] we distinguish between standard designs and design units. The standard designs encapsulate what is reused in several product families, whereas the design units are elements which are not reused. The distinction between standard designs and design units is of importance as their nature is different. Standard designs have to be designed in such a way that they can be used in future products, whereas design units only have the scope of one product. Consequently the application aspects are different for standard designs and design units. A standard design requires a higher degree of documentation, higher degree of maintenance, appointment of responsibility than a design unit, in order to enable reuse in future products.
List of interfaces: This area described the important mechanical, electrical, fluidal and software interfaces between standard designs and design units.
List of product families that can be derived from the architecture: This area describes the functional aspect of an architecture and includes key properties of the individual products that can be developed e.g. cost, energy efficiency, footprint, fault tolerance etc.

3.3 Production/supply chain requirements

The purpose of the production/supply architecture is to describe the building principle for production and how it supports launches of the future derivative products. It means that e.g. flexibility and scalability is of high relevance.
Generic production flows: These flows describe the main production and assembly processes including the necessary production equipment. At the end of the production flows, the types of standard designs that can be produced shall be described. This indicates the flexibility of the production and shows what differentiates each variant and what is common.
List of equipment: This includes the production lines, cells, machinery, tools and fixtures, mapped towards future launches.

3.4 Road mapping – future launches

Future launches: Indicate which products and standard designs to be launched.
Specific product updates: This shall explain which products that shall be launched for each application area.

4 STATE OF THE ART

This section described significant contributions to the modeling of architectures in literature:
Modular Function Deployment: The modular function deployment (MFD) [3] builds largely on the methodology of the QFD method and on the formulation of eight so-called module drivers. The purpose of MFD is to enable cross functional teams (including mainly marketing, development and production personnel) to create a mapping from the physical structure of the products within a family to the functional structure of those products and to ensure that the functional structure corresponds to the demands of the customers. Modular Function Deployment method consists of five consecutive steps. Customer requirements are mapped to functional criteria and subsystem design characteristics and subsequently forming a physical design in which a modular architecture supports a carefully selected set of modularization incentives called module drivers.
Design Structure Matrix: This approach takes a starting point in the decomposition of a product into components/systems and an identification of interfaces/relations among these, Pimmler & Eppinger [13], Höltta-Otto & De Weck [14]. By the use of algorithms, it is possible to encapsulate components

into modules or chunks that are closely related to each other from an interaction point of view [15]. This process is referred to as clustering. The outcome of a DSM is a proposal for a future modular product architecture.

Generic Bill of Materials: The generic BOM originate from the assemble-to-order environment [16]. The end-products typically have a number of features for which a number of options are available to choose from. Not many options are required in order to make the number of combinations (i.e. end-products) enormous. The number of end-products can easily become too large to able to define specific BOM's for every single combination. Furthermore, forecasting, BOM-storage and maintenance become unmanageable. The generic BOM is a concept that is introduced to enable creation of a specific manufacturing BOM when the customer places an order. The generic BOM is used to describe related products in one all-embracing model by using generic and specific items.

Decision tree: The decision tree [17] is used by Tiihonen & Soininen [18] as a product configuration model, which basically represents all the valid combinations of the components that can be used to obtain the desired functions for the customer. The decision tree presents the multitude of component variety within a product family and by the use of positive combinatory relationships (e.g. if "engine size"=D13 then "engine power" must be 360 or 420 hp) and/or incompatibility relations (e.g. if "engine size"=D13 then "engine power" cannot be 220 or 700 hp) it defines the possible product configurations.

Value analysis: Value Analysis is a discipline founded at General Electric in the late 1940's [19]. In short, value analysis is a methodology that has as its purpose to relate cost with functions in a product. It is a stepwise methodology in which a product is partitioned into smaller constituents for further analysis – that may be analysis of cost or value. Value is not the same as the Japanese idea of customer value we may see within the lean paradigm. Value is specifically defined as the "worth" relative to cost, i.e. value = worth/cost. Worth in this sense actually resembles the idea of customer value in lean very well. It is a denominator of those aspects, functions and features a customer wants to pay extra for. Some practitioners try to quantify worth and relate it directly to cost. Obviously cost is rather quantitative and measurable in hard currency, while "worth" is a more soft and qualitative size. Whether qualitative or quantitative, value has a focus on identifying value elements from a customer perspective and relate it directly to the functions of the product and thereby indirectly to the way the products are built.

Function structures: The function-based design methods are characterized by establishing either a function model [20] or the schematics of the product [4]. The function structure describes the flow of material, data, and energy through sub-functions of the product using a set of rules (e.g. the rules that are referred to as the functional basis which basically is a common language to describe functional elements. The schematic of the product is somewhat similar to the function model. But where the function model describes the product using functional elements the schematics on the other hand can describe both functional and physical elements, whichever being the most meaningful. Having established an understanding of the functional structure of the product some methods base identification of modules on experience and some simple guidelines, i.e. a rather qualitative approach [4], [13] and [20].Basically, these methods identify potential modules in a way similar to the way the MFD method makes use of the so-called module drivers.

Multi criteria assessment: Otto & Hölttä-Otto [21] presents a technique based on multi-criteria assessment where product architecture concepts are given a score based on a set of different weighted criteria. Although, the method is designed to be used for screening of preliminary product architecture concepts, and not - as it is the focus of this research - analysis and re-design of product families, the method include analysis aspects that should be considered. The method is based on relatively quantitative metricc adapted from the field of modularity, product architecture design, and product development in general (e.g. functional structure, DSM, commonality indices, etc.).

Value stream mapping: Most value stream mapping tools has a focus on information and physical goods passing through the supply chain. The value stream is consequently often perceived as the flow of materials through the value adding processes. There are several value stream mapping tools, e.g. by Womack & Jones [22]. This section describes the "traditional" value stream mapping tool. Other tools or methods re describe in the subsequent sections. A less graphical depiction of the value stream is a process activity map. It is a schematic representation of the critical path of a production. It is basically a matrix containing a mapping between process steps and machines, time consumption and distance along with other factors of choice. This tool may be used in conjunction with the traditional value stream map or as a preparation of that.

Conclusion: It is clear that all the above approaches can play a role in identifying structural aspects of an architecture, but the functional aspects are not explicitly described. Furthermore the structural contents of architectures are not described in terms of different design types, e.g. standard designs and design units. This topic is relevant in order to design flexibility in product architectures. In large projects this plays an important role concerning scoping of the development task.

The next section will present a proposal for the modeling of market, production and production architectures.

5 ARCHITECTURE MODELING

5.1 Market architecture

The purpose of modeling the market architecture is to bring clarity into decision making concerning the choice of which segments to cover or not cover and what properties are needed in order to do so across different business areas with different applications. A clearly defined market architecture is able to guide and control the engineering efforts towards profitability by "smart" product family design.

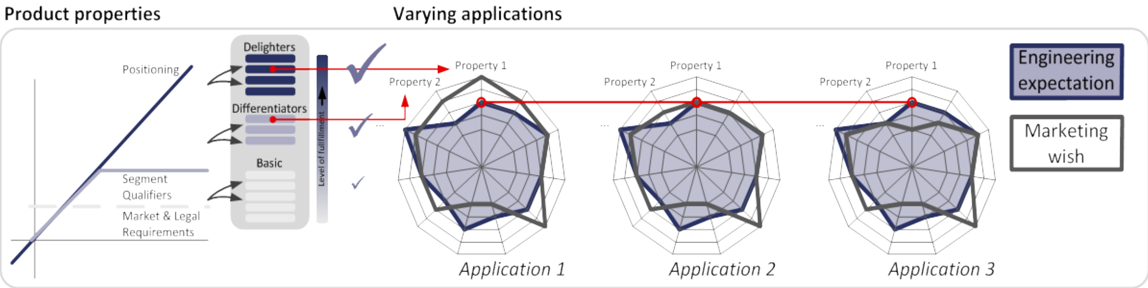

Figure 3. Product properties and their mapping towards varying market applications.

The radar diagrams show the total performance of the product by mapping the properties capable of positioning the product against competitors e.g. by differentiation. During the early phases of product scoping and requirements definition in close cooperation with competencies representing marketing, the mapping can serve as means of matching the wanted product performance from a marketing point of view with the expected product performance from an engineering point of view. Hereby, the explicit mapping can have a brokering function facilitating the meeting between sometimes unrealistic marketing wishes and best guess engineering expectations. If applied to a product family intended to cover different applications in different segments with varying requirements, it is of fundamental interest to map marketing professionals' perception of the spectrum of varying demands. As it is most often impossible to fulfill requirements for all segments, the mapping can help focusing the product architecture towards the most appropriate and favorable segments. To concretize the product properties, features and options can be modeled e.g. by the means of the "customer view" [7] mapped towards the different applications and varying the performance levels (low-, mid- and high end).

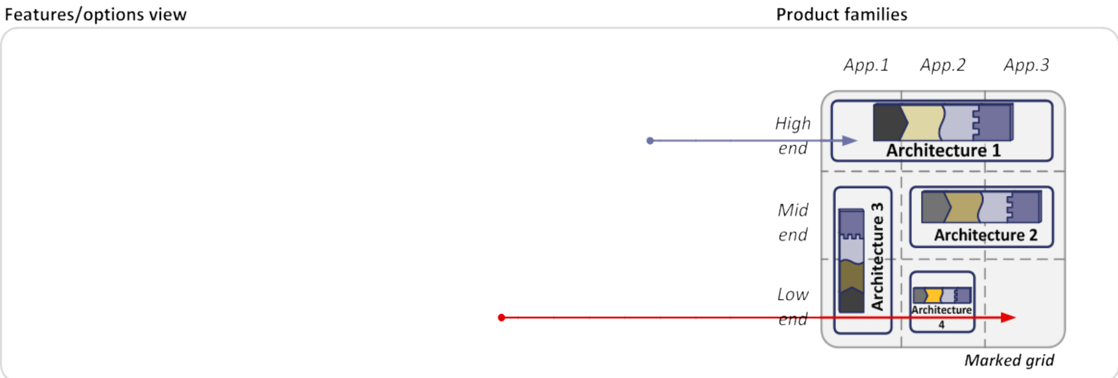

Figure 4. Features/options and their mapping towards performance levels in different applications and the identified product architecture(s).

This mapping serves to answer the questions of which product features that are in scope for the development task. Some features are too expensive or simply irrelevant for certain applications and are outside scope. Other features will be outside the standard program for all applications since they may ‘pollute’ a robust product architecture. Finally, the mapping towards one or more product architectures closes the gap towards engineering and sets the boundaries for the development task.
The detailing of the link between matching product features and identified product architecture, calls for a visualization of the commercial variants. They serve as being the ‘contract’ between engineering and marketing explicitly identifying the development task. The detailing of this list requires the product development task to be past the early stages, but major value is represented in conducting this modeling as early as possible.

Figure 5. Commercial variants and their utilization of standard design, design units and associated product features

The modeling will vary according to the application variation, general market aspects etc., however, the models shown in Figure 3, Figure 4 and Figure 5 are made to illustrate the general purposes.

5.2 Product architecture

According to the suggestions presented in this article, the modeling of product architectures encompasses the constitutive structural elements of a product architecture and the behavioral functional abilities. In other words, the aim of this model is not solely to describe what the product architecture *is*, but also what the product architecture is able *to do*.

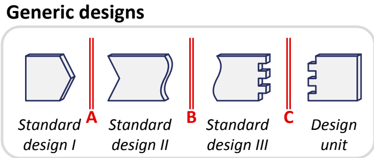

Figure 6. Generic structural elements of the product architecture: Standard designs and design units.

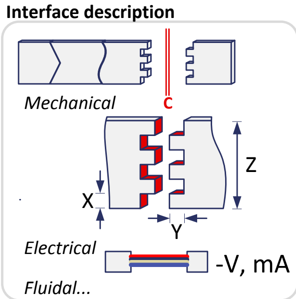

Figure 7. Modeling of interfaces between standard designs, between standard designs and design units and/or surroundings.

Equally important to the standard designs and design units, the interfaces capable of maintaining a predictable product structure, must be modeled explicitly as well.
Different standard designs can adopt different roles. Some are closely related to specific functions and/or application, while others are universal to the product architecture. Finally, design units are used for embodying functionalities that vary between individual product variants.

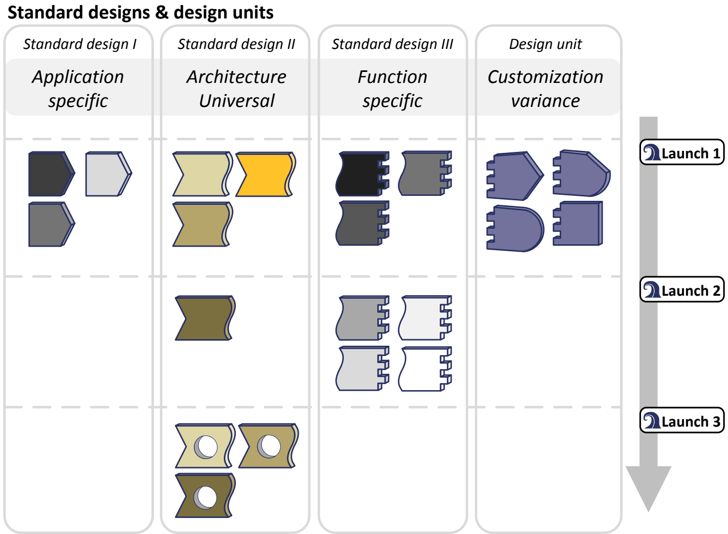

Figure 8. Standard designs & design units.

Figure 8 shows the variance across the different structural elements while incorporating the dimension of future launches: Which designs need to be prepared for which launches? Naturally, it is impossible to plan further than a certain realistic extent in rapidly changing markets, but the higher the detail this modeling can achieve, the better the basis for improving the launch preparedness is.

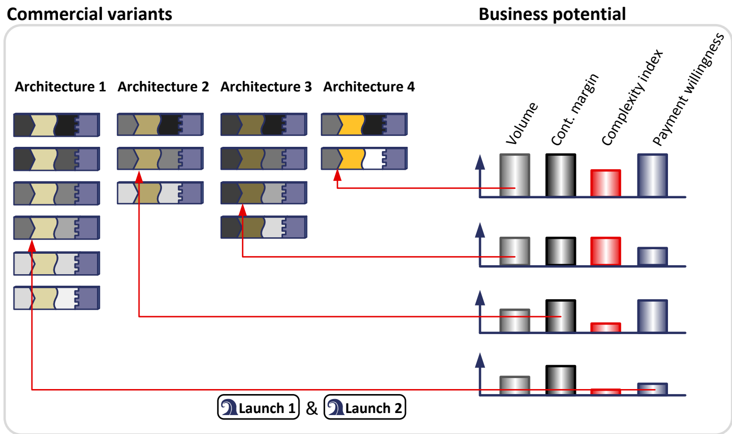

Figure 9. Assessing the business potential of commercial variants.

As described earlier, the explicit modeling of commercial variants early in the development process, act as the explicit link between the market- and product architectures, it is of fundamental commercial importance to map the expected production volumes, contribution margins, and payment willingness from customers – the payment willingness being the quantitative interpretation of the 'worth' phenomenon described earlier. If established, a measure of the complexity induced by different product variants can be included to qualify discussions with industrialization professionals with the task of freezing production architecture aspects. These four measures can help balancing out the product architecture(s), ensuring a leveled variance spectrum composed of "smart" variants with an appealing overall business justification.

5.3 Production architecture

Depending on the size of the product architecture development project, the associated production system will need either an update, a modification or a complete redesign. The production system is designed coherently, as the product architecture matures and passes from concept to detail design.

As basis for the modeling of production architecture is the generic production flow shown in Figure 10. This is capable of showing how and when the product variants are created in the production lines, which elements in the production system that are alike and which elements that differ. The relevant decoupling points (either *variant creation points* or *customer order points*, depending on the context) can be established and fixed. Furthermore, an inclusion of relevant machinery, tools and capacity utilization metrics provides the opportunity of assessing key financial characteristics of the suggested setup.

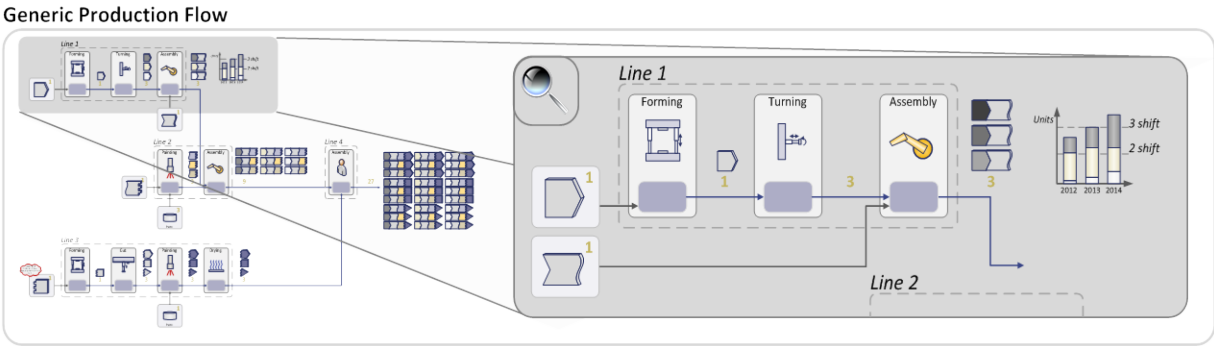

Figure 10. Generic Production Flow: Modeling the flow of all variants in one visual model

Since production equipment can require extensive capital investments, a mini roadmap of the lines, machinery and tools is valuable to map towards the suggested launch rhythm. As shown in Figure 11, the addition of further parts and components intended for launch 3 and beyond, will most likely entail a larger utilization of the production capacity, take up physical space of the production floor and require additional investments in machinery and tools downstream.

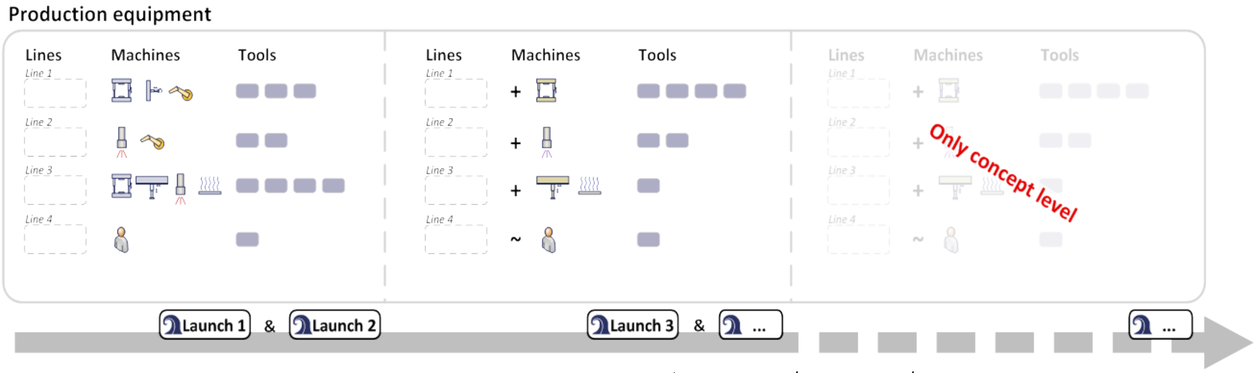

Figure 11. Production equipment needed for 1st launch, 2nd launch, 3rd launch etc.

These are all aspects that are predisposed by the design of the product architecture(s); thus requiring explicit and coherent models.

As marked in Figure 4, certain features will be part of the standard program incorporated in specific commercial variants, while other features will need an individual business case in order to be fulfilled as e.g. customizations. Setting up a global chain of supply and delivery, service levels of standard lead times, degree of local customization possible etc., are also factors predisposed by the architectures of the product and production. Figure 12 shows an example of how a global company could utilize the price of cheap labor in some regions with the local capability of customizing product (and perhaps conduct final assembly) around the world in product/distribution centres.

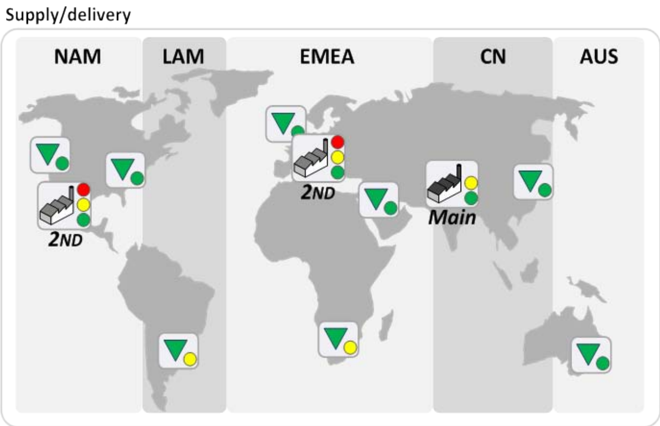

Figure 12. Global supply and delivery capabilities

5.4 Roadmap

The behavioral aspects of the market-, product- and production architecture is considered in the architectures' future launch preparedness. This is a function of the architecture, explaining what the architecture is able *to do*. This ability is modeled by visualizing the launches, derivative products and specific product updates – already planned for.

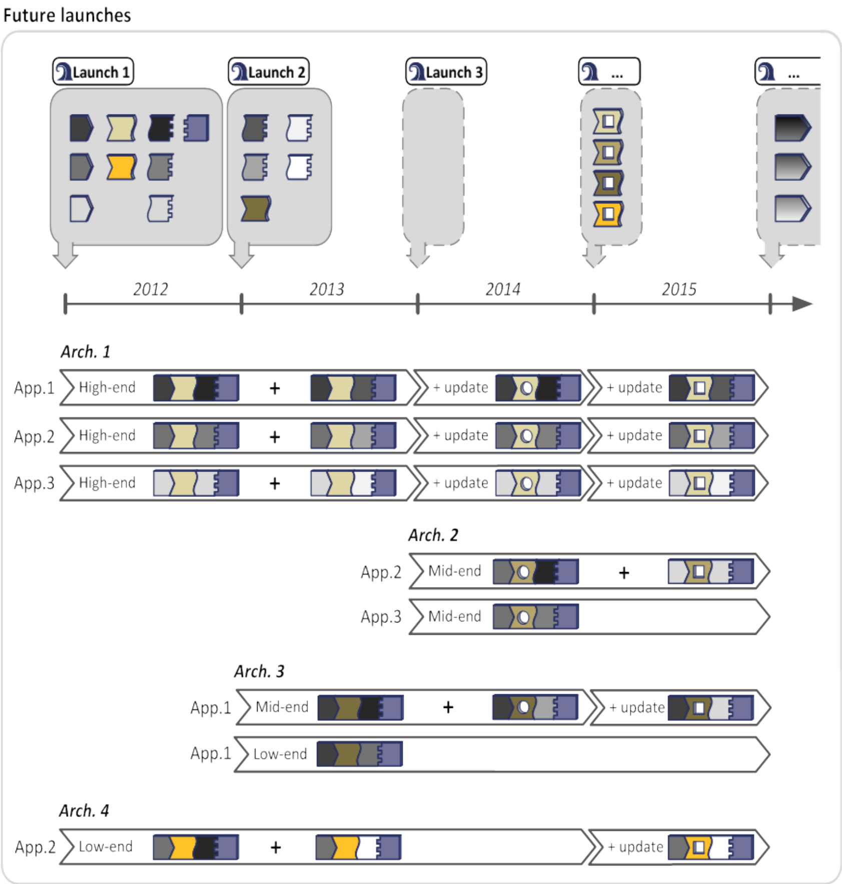

Figure 13. Future launches:
Launch preparedness, launch waves, derivative products and specific product updates.

6 EXPERIENCE FROM APPLICATION

The above architecture modeling approach has been utilized in one large scale product development project. The case company is operating globally and develops industrial products in high volumes. During the 2 year project, approximately 100 designers have been working on developing the product program. The development project has included complex fluid-dynamics, mechanics, materials, software, electronics, solid state mechanics and thermodynamics - architecture wise only mechanics and electronics have been included. In the area of production, complete new facilities have been established in Asia, Europe and the US. Market wise the product program has partly been launched. Sales is taking place through existing sales companies. The application areas include mainly existing well known areas, but also a few new applications are included, e.g. renewable energy.

The PhD students have been working for more than a year and a half, several days a week in utilizing the market, product and production architecture model. During the case study, the architectures has been developed and described by the PhD students in close collaboration with employees in sales, product management, engineering, production and supply chain. Four types of architects have been responsible for the contents of the market, product and production/supply chain architecture. The four types of architects are named market, product, production/supply and cross functional architect. The market architect is based in product management and is responsible for the market architecture and roadmap; the product architect is based in engineering and is responsible for the product architecture; the production architect is based in production and is responsible for the contents of the production architecture; and the cross functional architect is responsible for the alignment of the market, product, production architecture and roadmap. The project manager has acted as the cross functional architect.

Two kinds of meetings have been conducted in the project: They are named architect meeting and cross functional architect meetings. The first year both architect and cross functional architect meeting was carried out each Thursday from 9.00 to 11.00. During the last period the market, product and production architect was held each week, but cross functional architect meeting was held every 2nd week. Participants in the market architect meetings were program management and product management. In the product architecture meetings, senior designers from relevant specialist areas participated. In the production architect meetings new product introduction managers, tool designers and production line designers participated.

Experience from application of the market architecture: The feature/options has enabled an earlier and more explicit definition of what defines a high end, mid end and low end product, i.e. clarification of which features and options that shall go into which variants.

Experience from application of the product architecture: The interfaces have been decided much more conscious compared to previous projects in the company. It means that the next 3 product launches have been explicitly planned in such a way that the architecture is prepared for one new technology, an update of the user interface and more advanced wireless communication.

Experience from application of the production architecture: The project has had the task to establish completely new production lines with three kinds of automation levels, fully automatic, semi automatic and manual production and assembly. Particularly the full automatic production line design have benefitted from the product architecture. It has been possible to order new production and assembly equipment earlier since the product program have been decided earlier and therefore variety of each part have been known earlier. Also the product architecture specification has been beneficial to production design since flexibility and scalability is very important design properties for automatic production equipment.

Experience from cross functional application of the market, product and production architecture: The main benefit of the cross functional review meetings have been continuous scoping of the project, i.e. decisions concerning what shall be developed now and what shall be postponed. Another aspects that have been more consciously considered, is clarification of where the architecture shall be prepared and where is shall not be prepared for future launches. The performance limits concerning cost, energy, foot print and availability have also been clearly defined.

All in all the main benefits of applying the explicit modeling of market-, product-, production architectures (including the roadmap) has been a contribution to:

- Improved preparedness for future launches, e.g. user interface and improved energy efficiency.
- Improved synchronization between product- and production development
- Achievement of attractive cost- and technical performance level on all products in the product family
- On time launch of the generation of the product family

Concerning future application the cross functional architect role has to be reconsidered. With a traditional organisation, one could argue that “no one” or everyone is responsible. No single person or department have all the competencies necessary to handle the cross functional architect role. This will be a topic for further research and case studies. The architecture models are mainly handling technical decisions whereas business decisions are only implicitly addressed. This is another area that obviously should be improved.

7 CONCLUSIONS

The paper has presented an explicit proposal for description of contents of a market, product and production architecture. The main contribution is the distinction between structural and functional contents of architectures. By this distinction it is possible to improve the description of what the architecture is prepared for concerning future launches.

Further work includes test in two other companies. So far only the mechanical and electrical elements are included. It is clear that also software has to be included in the next version of the architecture model. Also other life phases such as service/aftermarket will in many cases be of high importance. A follow up case study is planned in order to study whether the intended preparedness is realized in reality.

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