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# INTEGRATED AND CONFIGURABLE PRODUCT AND MANUFACTURING SYSTEM MODELS

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## 1. Introduction

Many automotive companies are developing products using a platform approach. Furthermore, the continued globalization of the industry require more collaboration between people working from different locations around the world. Collaborative distributed work relies heavily on the ability to support the necessary communications that are required to make progress. In order to facilitate this process there are (at least) two prerequisites. The first prerequisite is that there is an agreement on the methodology used to make progress. This is often referred to as a product development process and is in many cases defined and described using a stage-gate model. The second prerequisite is the availability of ways to define and describe the different achievements along the refinement process. The purpose of these definitions and descriptions is at least twofold: (1) to facilitate communication in order to establish a commonly agreed understanding of the emerging development results, and (2) to support an iterative, step-wise, and decentralized evaluation and optimization of the emerging development results. In this second prerequisite we find supporting tools and methods in terms of 3D CAD models, CAE models, product and process descriptions, etc. Even though there are many product development processes described throughout the world, there are still unresolved issues when it comes to apply them for high variety, platform-based product development scenarios. Additionally, a vast majority of tools and methods available to define and describe the emerging product are still limited to definition and description of a single design, i.e. one selected variant from the platform. For these reasons there is a need to revisit traditionally well-established product development approaches and their corresponding tools and methods from the perspective of a globalized product development perspective where we develop platforms with the intention that they will carry several derivatives potentially for several product brands. The content of this paper focus on the linkage between a product model and a manufacturing process model that accounts for a platform-oriented approach in each of the two domains. The paper furthermore presents an integrated model for dealing with platform-based, high variety products including the perspectives from development, manufacturing, and sales & marketing.

## 2. Context and rationale

Recent research papers and publications show that there is a lot of on-going research and focus around product families and platform development. A newly released book (Simpson et. al., 2006) provides a kind of a baseline for current state-of-art and made achievements regarding product platforms and product family design. A major difference when working with platform-based products is that it is necessary to go beyond the traditionally used single-product development approach where it was possible to step-by-step decompose the development and design tasks from business and market requirements to product requirements and manufacturing requirements. In platform-based development it is necessary to simultaneously consider and refine design decisions in several domains, e.g. market & business, manufacturing, and product design (see figure 1).

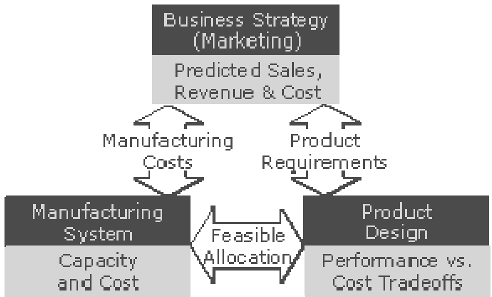


**Figure 1. Platform requirements require simultaneous considerations in several domains (Michalek et. al., 2005)**

Michalek et. al. (2005) states that the new era of globalization has influenced both product portfolio variety and the architecture of the manufacturing systems producing these products. Product designers are interested in reducing the cost of their products while offering product characteristics demanded by a heterogeneous market. Furthermore, there is a lack of tools and methods that incorporate quantitative models for making tradoffs between revenue and cost consequences of design changes. A negative consequence of this lack in support is the risk of making design changes that are less costly to manufacture, but also less desirable in the marketplace.

## 3. An integrated framework for product, process, and market definitions

A framework for a systems view on product development has been described in earlier papers and in a licentiate thesis (Claesson, 2004). This framework can be extended (figure 2) to include two more dimensions in order to make it a more complete framework for development of platform-based products. The lower left section (2,3,4,5) of the framework corresponds to the earlier presented systems view of the product. The lower right section (5,6,7,8) adds a manufacturing operations model to the framework. The top section (1,3,8,9) of the framework adds important elements for sales operations and market communications.

From a customer perspective, the features (1) and functions (2) provided by the product is most important, especially in the phase when the customer is considering buying a product. The customer expectations of the product properties (3) will not be really judged until the customer – after buying the product – uses the product for the purposes the customer intended when buying the product. From a business perspective, it is important that the customers expectations of the product properties when experienced in practical use of the product are met or even exceeded resulting in a satisfied or even delighted customer. In this context, features are those attributes of a product (i.e. a mapping of functions and/or properties) that are easily recognized and valued by the customer. Among these features is also included all the possible choices the customer is offered in order to define the appropriate product variant suitable for this individual customer from the product range and product variety offered by the company to its customers. From a product development perspective the range and variety of product functions and properties must be allocated and implemented by the set of components (5) that in a certain combination (i.e., configuration) define and implements a product variant. The definition of this allocation and mapping of implementation of functions and properties is referred to as the product architecture (4). The mechanism defined and proposed in earlier papers and in the licentiate thesis (Claesson, 2004) are to create a structure of configurable components (CCs). A configurable component structure share many similarities with generic product structures (e.g., Van Veen, 1990). However, there are some very important differences between a generic product structure (often referred to as a GPS) and a configurable component structure. Some of these similaries and differences has been outlined in a previous paper (Claesson et. al., 2005).

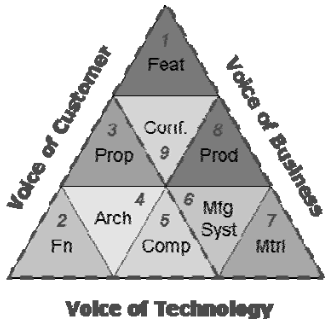


**Figure 2. Extended systems-oriented framework for development of platform-based products**

In order to make (i.e., manufacture) the product range and product variants defined through the set of components and the product architecture, the framework has been extended by the domains necessary to define a manufacturing system (5,6,7,8 in figure 2). The working mode of a manufacturing system (6) is essentially to consume and transform material (7) to products (8). This transformation is to be performed in accordance with the defined components (5) that are defined during the product development phase. The way this transformation is achieved is referred to as the manufacturing system (6). The manufacturing system can either be an existing system and pose a requirement on the product or be developed in concurrence with the product during the development phase.

The domains 2, 3, 4, and 5 of the framework is essentially a generic model of a system. It should therefore potentially also be possible to use a similar framework to define and describe the manufacturing system (domain 6 in figure 2). This approach is illustrated in figure 3, where the framework (2,3,4,5) has been adapted to a more manufacturing oriented language. By comparison, functions (2) are similar to operations (6a) in terms of that both represent something that the system is capable to do (perform). Furthermore, these operations must be allocated to some physical elements of the manufacturing operations in order to actually exist and be executable. In manufacturing the correspondence to the components (5) in the product are often referred to as equipment, tools, and different kinds of other resources (6b). Similar to the product architecture (4), the operations (6a) and equipment/resources (6b) in the manufacturing system must be organized in some way to actually deliver the expected outcomes. In the manufacturing system model this is achieved through the definition of a process structure (6c) that provides the necessary linkage between operations (6a) and equipment/resources (6b). Again, similar to the systems view of the product the manufacturing system in operation (use) will have a certain set of characteristics or properties (6d) that are either those designed for and thus expected or in a less successful case not exactly those expected and/or required. Manufacturing system properties that do not meet expectations or requirements can impact either the business operations (in terms of too low manufacturing performance from a business perspective) or the customer (in terms of quality issues in the manufactured and delivered products) or in worst case a combination of both. Given the importance of the manufacturing system and its properties it is clear that development effort and focus of attention must be given to the system level design of the manufacturing system as well as to the complete system level of the products.

The third piece of the framework is the connection between the features (1) that is the description of the product most natural and closest to the customer with the manufacturable products (8) through a configuration (9). The configuration domain provides a mapping from a set of features to the definition of a manufacturable product variant. In many cases a similar functionality would be referred to as a sales configurator or customer specification support system (CSSS, Van Veen, 1990). Even though it is of great interest to explore this piece of the framework further it is out of scope for this current paper. The reference to existing approaches for sales configurators will have to do for now as a temporary description of this piece of the framework.

The focus of this paper – besides presenting the above mentioned framework – is to outline further the manufacturing system model and its linkage with the product model in the framework. First, however, a short recapture of the configurable component concept is presented followed by the presentation of the manufacturing system model.

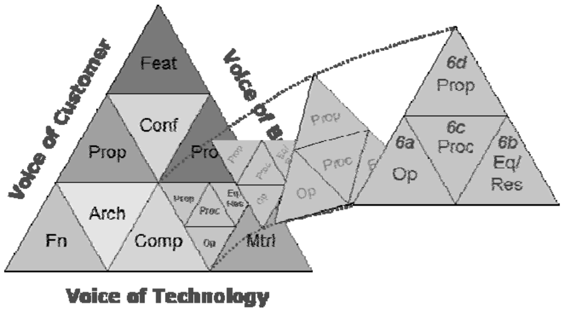


Figure 3. Expanding the systems view of the manufacturing system

## 4. Configurable Components

The concept of configurable components (CCs) has been introduced and described previously in several papers and is further defined and described in Claesson (2004). Figure 4 provides a short overview of the concept and illustrates also the important feature of the concept to capture an entire platform structure using a very compact notation and the use of the configuration and instantiation mechanisms embodied in the concept to instantiate a (partially) configured (potentially intermediate) structure depending on the task at hand. Figure 4a shows an overview of the concept with a configurable component structure composed of three CCs where the top CCs is defined to use the two bottom CCs (of course depending on if the applied configuration criteria determines that any, both, or none of the two need to be used). Each CC has a variant parameter interface (VPI) through which the configurability of the CC is presented to a user of the CC and through which a configuration (and instantiation) request of the CC can be made. The internal structure of a CCs have several important elements. For illustrative puposes the figure 4a shows two important internal features of a CC – a configuration rule set (CRS) and a set of embedded design solutions (DS). The embedded design solutions, DSs, carry the parametric design definitions that define the CC's capability to act as a design solution in some context. The provided parametric definitions for the design solution, in turn, define the configurational capabilities of the CC (i.e., the design bandwidth for the CC). The configuration rule set (CRS) define the mapping between the provided configurability of the CC through its variant parameter interface (VPI) and the required design parameter values of the embedded parametric design solutions (DSs) to respond to the requested configuration. The configuration rule set (CRS) furthermore determine (in collaboration with the parametric design solutions, DSs) the mapping and definition of the variant configuration requests (VCRs) that allow the CC to utilize other configurable components in the structure in order to fulfil its mission as a design solution in a specific context. The variant configuration request (VCR) determine both whether the related underlying CC should be used or not and if used, it requests an appropriate configuration of the related CC through its VPI.

Figure 4b shows a very simplified and tentative car example created to illustrate the compact notation and the resulting structure after applying a (potentially incomplete) configuration criteria (an instatiation operation is mostly embedded in the application of a configuration criteria). The top view of figure 4b show the three CCs defined in this small example – a CC(car), a CC(Door System), and a CC(Door). Since we make effective use of the configurability mechanism of the CCs we only need one definition of a car door, even though there in most cases may be either 2, 3, 4, or 5 doors in a specific body style of a car. A 2 door sedan, a 3 door hatchback, a 4 door sedan, or a 5 door wagon. The lower view of figure 4b show the effect of applying a configuration criteria (and the embedded instantiation). The resulting structure illustrates the potential existence of 5 door instances (two front side doors 1 & 2, two rear side doors 3 & 4, and a rear door 5 in the case of a wagon or hatchback). The 'u' letter in front of the rear side doors and the rear door reveals that the applied configuration criteria did not include any information as to whether these doors should be included in the configuration or not. Further, the lack of any letter in front of the two front doors indicate that these two are mandatory in any structure (a design decision embedded in the definition of the door system CC). Last figure 4c shows the recursive top-down configuration and instantiation scheme defined within the CC conceptual framework. Several potential configuration and instantiation schemes can be envisioned when the CC concept is further developed and refined. In this case a simple depth-first traversal of the structure was used.

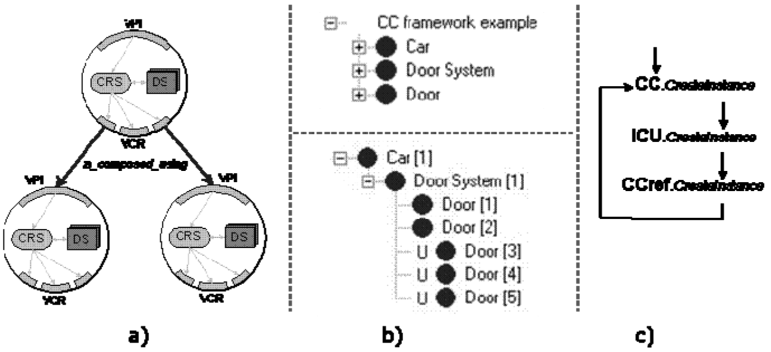


**Figure 4. Overview illustration of the configurable component concept**

From a design methodology point of view, the CC concept has been presented as a complement to existing well-established design methods. One suitable method to use as a foundation for the application of the CC concept is the function-means based design approach. A possible approach to utilize the function-means based approach extended with the CC concept has been described by Johannesson and Claesson (2005). The linkage between the CC concept and the function-means based model is illustrated in the right part of figure 5.

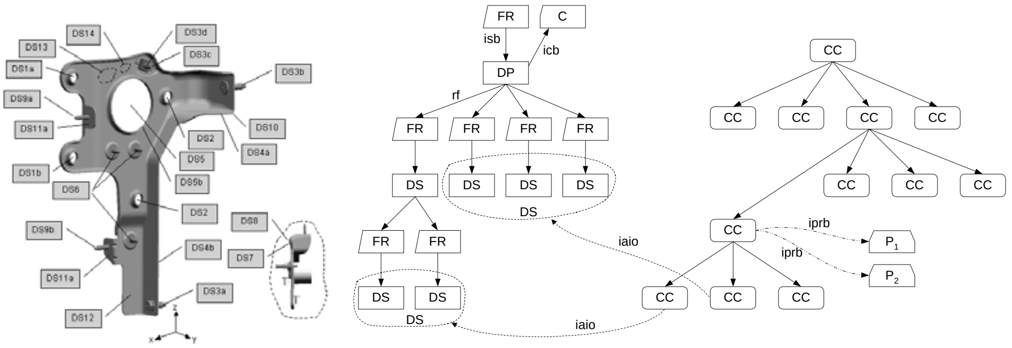


**Figure 5. CC enhanced function-means based reversed engineering example**

The CC enhanced function-means based approach has been used in a small case study where a cross-car beam has been investigated regarding possibilies to improve the design from a platform-based perspective where the objective was to try to find approaches to increase the design bandwidth of the cross-car beam assembly as a whole as well as for the components within the assembly. Figure 5 shows an example of reverse engineering effort where the different elementary design solutions of a cross-car beam bracket was identified and enumerated. The example is only included here in order to serve as an illustration of how the CC concept is related to the function-means based approach as well as to the elementary design solutions embedded within the scope of a single designed part.

## 5. Extending the CC concept to the manufacturing system domain

The second main purpose with this paper is to provide a description of how the general mechanisms embodied within the CC concept can be adapted to provide for a configurable manufacturing process model. In the following we will have to distinguish between two types of CCs – a product CC denoted $CC_{prod}$ and a process CC denoted $CC_{proc}$. The configuration capabilities of a process CC (figure 6) will be used in order to configure the process to a manufacturing facility, to configure the facility to match the required execution environment for the process, as well as to configure the appropriate behaviour of the process in a certain context.

There are several available approaches to model the behaviour of an operation. Some form of Petri-net oriented approach to define the behaviour is the most likely approach to model the behaviour. The CC concept presented here is, however, not depending on the approach taken for the more detailed modeling of the behavior within a defined process or operation.

Figure 6 uses two product CCs and one process CC to illustrate the approach to link the product and process structures. The top-most product CC is materialized (i.e., produced) by the process CC. Through the materialize (…) request, the product CC provides enough configuration parameters to the process CC to enable it to be sufficiently configured to perform the operation of delivering the requested physical representation of the product CC (illustrated with the darker box inside the product CC). The process CC, in turn, can forward the execution request with required parameters to underlying (not shown in figure 6) process CCs and potentially to other product CCs that carries the ability to be physically instantiated (illustrated with the lower product CC in figure 6). Through these mechanism a recursive configuration and instantiation pattern will evolve through-out the structure in a similar way as previously shown with the simple car door example (figure 4).

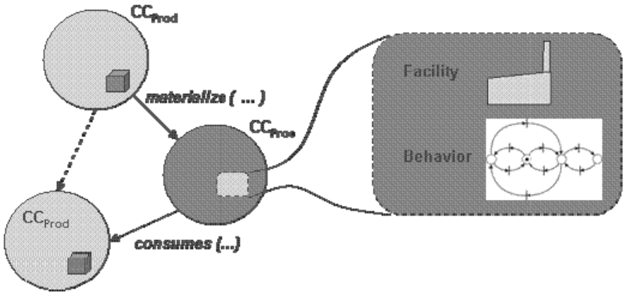


**Figure 6. Illustration of product CC and process CC**

Figure 7 provides illustrations of how the configurable process concept is intended to be applied in order to model manufacturing processes and operations. The left part of figure 7 illustrate that the configurable process will be linked to different manufacturing model elements and be used in order to deploy and configure these elements (in the case they as well are modelled as being configurable) in order to provide an appropriate context for the execution of the configured process. The essential part the figure intends to illustrate is that the model is defined as a true pull flow, where the pull flow in this case also include the propagation of the configuration parameters through the two linked structures. Thus the configuration of the resulting part requests the configuration of the configurable operation, which in turn request the configuration of all the associated resource elements as well as the required material in terms of the WIP being refined and any additional materials required to perform the operations. In the model shown an actor can be either a person or any kind of automated equipment (e.g., a robot or a robot cell). Tools in this context are those items that are in actual contact with the WIP and other materials being subject to the refinement activities in this operation. The illustrated model is not a complete model. There are additional elements required in a more complete model. The elements presented are the essential elements required in order to illustrate the intentions behind the presented configurable process platform model.

The right part of figure 7 illustrate how the configurable process will be used in an assembly line model. Given the capabilities and model structure illustrated in the leftmost part of the figure, the configurable assembly operation will allocate itself to the appropriate station along the assembly line and configure this station in order to provide an appropriate environment for the execution of the operations embedded in its definition.

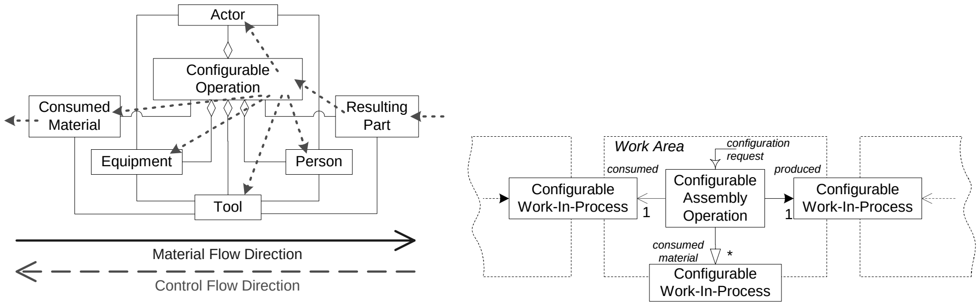


**Figure 7. Model examples of configurable process CCs**

## 7. Process platform

Jiao et. al. (2006) provide an overview on process platform and production configuration for product families. Jiao et. al. recognize and makes a point that it is at the production stage that product costs are actually committed and product quality and lead times are determined *per se*. This implies that the true benefits of a platform-based approach can only be fulfilled at the production stage. As a consequence, it is as important to be able to model configurable process platforms as it is to be able to model the configurable product platforms.

A tentative model of a configurable process platform is illustrated in figure 8. The model is created using the process CCs as model elements and is an attempt to model a vehicle manufacturing process from a configurable platform-based perspective.

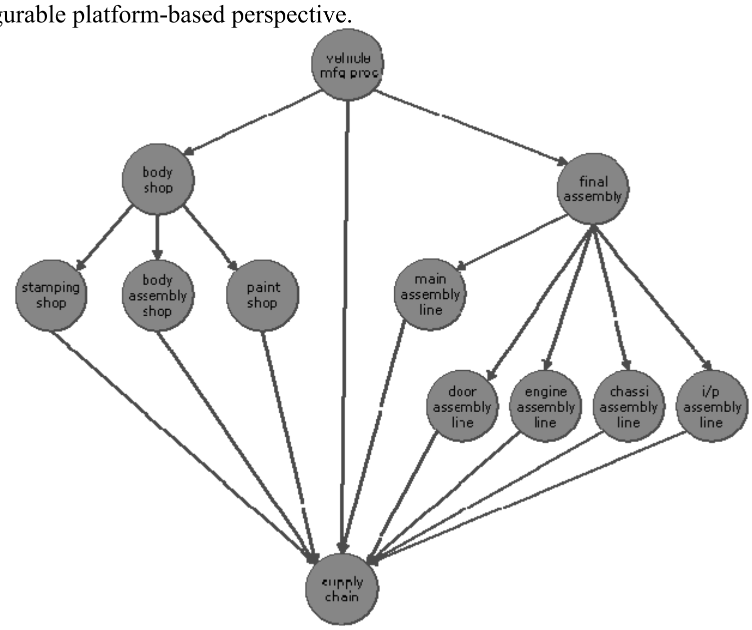


**Figure 8. A tentative configurable process structure for vehicle manufacturing operations**

The proposed model in figure 8 will be evaluated in an upcoming case study where a number of different body styles will be used as an example problem to illustrate and evaluate the use of the combined product CC and process CC modeling capabilities.

The body assembly operations for three basically different body styles – a sedan, a wagon, and a cabriolet (figure 9) – will be used to create an example of a combined configurable product and process structure using the approach outlined and presented in this paper.

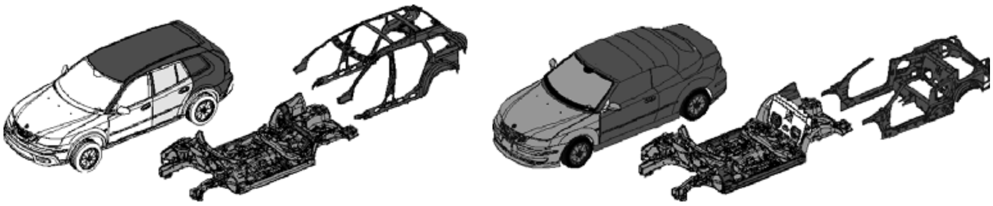

**Figure 9. Body assembly differentiations for a sedan, a wagon, and a cabriolet**

## 8. Conclusions

The paper has outlined how to extend the previously introduced configurable component concept to span both the product and the manufacturing process domains in order to provide configuration capabilities that effectively can capture and define product and process variety required for a platform-based product development. The format of the paper does not allow for a comparision with other related work within the area (e.g. Jiao et. al., 2006). An important difference is the utilization of the configurable component concept as the foundation for the modeling. The CC concept is similar to the generic product specification (GPS) concepts (e.g., Van Veen, 1990). The CC concept, however, is different from the GPS concept in several important aspects. These aspects are considered to be of importance both in terms of the capabilities offered by the modeling concept, but maybe even more importantly when it comes to efficiency in terms of administration and compactness of the structure definitions offered to an organization that have to deal with large scale development of complex products in a global context with many manufacturing locations to consider. One important difference is the ability to provide decoupling through encapsulation and self-sufficiency that is offered through the CC concept. These features are not readily achievable in the GPS conceptualizations described in the literature. This decoupling is considered to be essential in order to provide robustness to the product and process models that, for instance, can reduce change propagation effects.

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