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# PLM SUPPORT FOR DEVELOPMENT OF MODULAR PRODUCT FAMILIES

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## ABSTRACT
Most modern manufacturing companies use a PLM/PDM system for documenting and managing product data. Companies use their PLM/PDM system for management of CAD files, documents, and drawings, but they do not take advantage of the full potential of the system to support modularisation. The objective of this research is to develop an approach for improving the role of PLM/PDM systems as supporting tools for developing modular product families. The approach is based on a visual product architecture model; representing a product family seen from a functional system perspective and a physical modular perspective. By means of a software program, product structures visual modelled can be imported to a PLM system, forming so called upper structures. Data associativity between upper structures in the PLM system and CAD models is described, as well as other types of associated product information. The key result of the research is the approach of using companies' PLM systems to build up and define product structures that support the activities of creating modular product families.

*Keywords: product families, product lifecycle management, product architecture, modularity, interface management*

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# 1. INTRODUCTION

The manufacturing industry has in decades been an intensive user of data-systems to drive quality and efficiency, adopting information technology (IT), and automation for design, production, and distributing products. It is hence not new that manufacturing companies use IT systems to manage the product lifecycle, including computer aided-design (CAD), engineering, manufacturing and product management tools (Manyika, 2011). Product Data Management (PDM) emerged in the late 1980s as manufacturing companies recognised a need to keep track of ever growing volumes of design files generated in CAD systems. PDM can in many ways be seen as a subset of modern PLM systems (Product Lifecycle Management) (Sääksvuori & Immonen, 2008), and is in this paper treated as so. The main idea behind PLM systems is that companies can create more value by integrating data from multiple systems. This is done by obtaining synergies of all available product related data, and to eliminate redundant data existing in different system environments. PLM is often described as an integrated, information-driven strategy of managing the whole life cycle of a product starting from generating an idea, concept description, business analyses, product design and solution architecture, technical implementation, and product testing, to the entrance to the market, service, maintenance, product improvement, and recycling (Stark, 2007). A concurrent initiative which the manufacturing industry has picked up in the last decades is the initiative of multi-product development/development of product families. The approach, described by many authors, strives to create variety at low cost by utilising commonalities or synergies between products and/or processes (Ericsson & Erixon, 1999; Harlou, 2006; Hölttä-Otto & de Weck, 2007; Martin, 2002). Product families can be defined as the products that share a common platform but have specific features and functionality required by different customers. While a subset of a platform is defined as the subsystems and interfaces common to all products in the product family, the central aspect of modularisation has to be addressed. The outcome of modularisation can be seen as the encapsulation of complexity by breaking down systems to manageable parts i.e. a modular structure. The activities of handling product development, and the related production development, are influenced by the degree by which the components and modules are coupled. Moreover development activities are influenced by the degree by which the components are re-used or pre-used in a number of products. The main hypothesis of this paper is that proper application of modern PLM systems can enhance the success of modularisation. This can be achieved because a PLM system is a strong tool not only for managing product data, but also for documenting modular structures, supporting concurrent engineering, and managing the variants of systems, modules, and interfaces within a product family.

## 1.1 Research Motivation

There seems to be some key reasons for developing and describing an approach for using PLM systems to support the development of modular product families. The challenge that companies face is, among others, the lack of integration between module data only present in the PLM/PDM system and the information about the modules that is captured in CAD. Some of the consequences of not having properly documentation and not having aligned data when developing modular architectures are:

- Difficult to recognise and manage modules and interfaces.
- Difficult for designers to find and re-use existing modules.
- Unclear what is standard and what is customised for a specific project or product.
- Difficult to carry out proper monitoring of relational properties and design progress during a project (e.g. cost of modules).

The research question which the authors seek to answer in this paper is: *How can PLM systems support the development of modular products?* The research belongs to the area of designing i.e. the aim of the research is to improve the design activity, and the effect on practice, directly or indirectly, is addressed in the descriptions of results.

# 2. ADJACENT FIELDS OF RESEARCH

In order to clarify aspects relevant to this research, the following section is recording briefly some main contributors to this area. The themes of the contributions include:

## 2.1 The introduction of enterprise PLM systems in companies

PDM technology is intensively used in industry and today its application is mainly focused on particular product lifecycle phases, e.g., development, prototyping, or production (Abramovici, 2007; Sääksvuori & Immonen, 2008; Stark, 2011). In recent years PDM vendors and integrators have found a multitude of acronyms, e.g., PDM Link, Team Center PDM, Collaborative Product Development (cPDM), 3D Product Lifecycle Management (3D-PLM), or Virtual Product Development (VPDM). In reality acronyms and descriptions are converging to PLM. PLM is the extension of PDM towards a comprehensive approach for product related information and knowledge management within an enterprise. This includes planning and controlling of processes that are required for managing data, documents and enterprise resources throughout the entire product lifecycle (Abramovici, 2007).

## 2.2 Modularisation

Modularisation is used as a foundation for identifying and developing product architectures and standard designs (Harlou, 2006). The sub-systems in modular product architectures are referred to as modules. One of the most common explanations of a module is provided by Baldwin and Clark (2000), who define a module as an unit, whose structural elements are powerfully connected among themselves, and relatively weakly connected to elements in other units. This explanation can be used to describe the essence of modularisation, because the split between generic and variable characteristics is possible due to the level of integration between the elements and units. Several authors describe approaches for developing modular products, which can assist in the development process (Erixon, 1998; Krause & Eilmus, 2011; Steward, 1981) .

## 2.3 Product architecture

In order to account for the relations between the meetings encountered by a product through its life cycle phases, structures can be defined for every life cycle phases, which are to be taken into account during development (Andreasen, Hansen, & Mortensen, 1996). The alignment of structures of the life cycle phases may be outlined as architectures. One definition of architecture is that it is a “purposefully aligned structure of systems” (Andreasen, Mortensen, & Harlou, 2004). The product architecture defines the basic building blocks of the product. Both in terms of what they are able to do, and what their interfaces with the surroundings and the rest of the device are (Ulrich, Eppinger, & Goyal, 2011). To sum up, the product architecture holds the information on how many commercial variants the product family consists of, how many components the products consists of, how these components work together, how they are built and assembled, how they are used, and how they are disassembled.

## 2.4 Interface management

Interface management deals with the issue of component integration (Sundgren, 2003). Component integration is the process of identifying all functional and physical characteristics of interacting entities from different organisations. Furthermore it is to ensure that proposed changes to characteristics are assessed and approved before implementation. Interfaces can be understood as linkages shared among components of a given product architecture. Depending on the level of analysis, a component can be a part, a module, a sub-system, or system (Mikkola, 2001).

## 2.5 Model based definition

Model-based definition (MBD) is a new strategy of PLM based on CAD model’s transition, from simple gatherers of geometrical data, to comprehensive sources of information for the overall product lifecycle. With MBD, most of the data related to a product are structured inside native CAD models, instead of being scattered in different forms through the PLM database (Alemanni, Destefanis, & Vezzetti, 2011).

## 2.6 Conclusion

All of the above described research areas are related to the approach and model described in this paper. The approach is grounded in an enterprise PLM system that is customised to support the functionality of handling a product seen from a functional system viewpoint and a physical modularisation viewpoint. The approach encompasses a representation of a visual product architecture to model the product components, their arrangement, and the interfaces among them. The PLM system can be used as an operational interface management system ensuring that components, modules, or sub-systems are compatible. The approach cannot be characterised as a MBD, because data is not structured inside CAD models. It can instead be characterised as an architecture based definition, in which product data is structured according to systems, modules, and their interfaces.

## 3. APPROACH FOR PLM SUPPORT FOR DEVELOPING MODULAR PRODUCT FAMILIES

The assumption behind this research is that visual product architectures in a beneficial way can assist the development of modular product families, because they model the product system in an explicit way. This creates overview of the products in the product family, and provides a basis for creating modules that are interchangeable when relevant. Most companies are already using a PLM/PDM system to manage product data in the development process, and there is a need for expanding the utilisation of these IT systems to also support the creation of modular product families. This section is presenting the approach of realising this. The product model formalism is based on the prior work of Harlou, but has been enhanced and expanded to cover a multiple structures view. The functionality of loading the IFD modelled structures into a PLM system, and the functionalities made possible in the PLM system, belongs also to the results of this research.

### 3.1 High level approach steps

The first step in the approach is to establish an architecture representation of a product family by means of the Interface diagram formalism (IFD) (Bruun & Mortensen, 2012a; Bruun & Mortensen, 2012b). Concurrent with this, a platform is set up in the companies PLM system in order to prepare the alignment with the objects defined in the IFD. In this research study PTC's Windchill 9.1 was used for the approach. In collaboration with the software vendor, functionalities were added to the commercial version for loading product structures defined in the IFD. By means of a small written software program the modelled structures from the IFD, made in Microsoft Visio, were retrieved and output was generated in XML-format, which could be imported to the PLM system. This upload is only performed one time, and further updates and alignment between the IFD and the PLM system is done manually with support in comparative reports. A comparative report is automatically generated and compares the structures from the IFD with the upper structures in the PLM system, outlining differences between them. In the user interface of the PLM system it is possible to link product information files to the structures. The structures become placeholders for information as CAD, design specifications, interface descriptions, purchase specifications, drawings, diagrams, test protocols etc. The structures are denoted Upper structures in the PLM system.

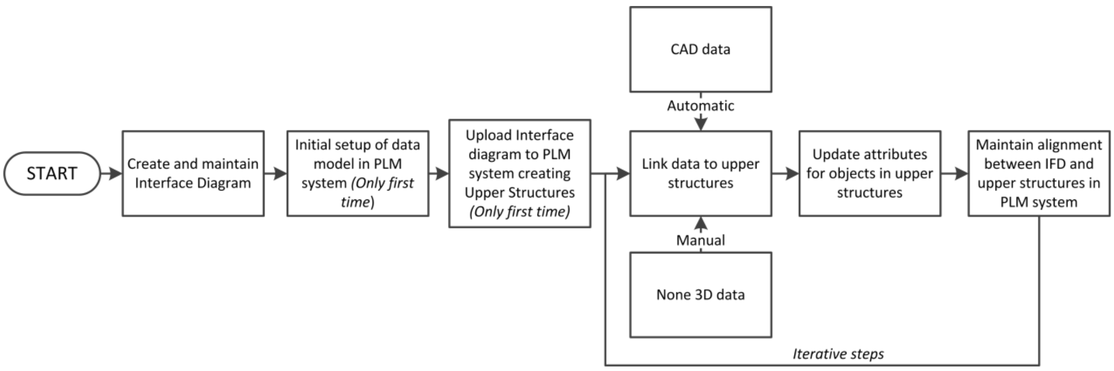


*Figure 1. Simplified process model for bringing modularisation into a PLM system*

Attributes like cost for objects in the PLM system can be assigned independent of the existence of CAD data for the object. This enables that a 'likely cost' can be monitored very early in the design phase. During the development process the IFD is updated while the design is matured and decisions on solutions are incorporated. These updates have to be reflected in the PLM system, and is done be comparing the structures modelled in the IFD with the structures established in the PLM system. As mentioned, this process is done manually by the support in comparative reports that outline which objects have to be added or removed from the upper structures in the PLM system.

### 3.2 Design management by IFD

The approach of using PLM system functionalities for supporting development of modular product families is made possible by the means of the IFD. An IFD is a visual product architecture representation, capturing structural characteristics of a product family, mostly combining the aspect of mapping between technology domains, and mainly a mapping between physical structures. The model puts emphasis on managing interfaces between components in the model, hence the chosen name of the modelling tool. The formalism has its basis in the Generic organ diagram presented in the work of Harlou (2006). Because of secrecy issues for the company involved, the formalism is illustrated and described by using an example of an IFD for a product family of Bobcats. The model puts emphasis on handling the product family seen from different viewpoints. The main viewpoint is a system perspective i.e. the perspective that deals with the product's main functions or its related lifecycle. Figure 2 (left side) shows the architecture of two of the systems in the Bobcat; the hydraulic system and drive train system. The two systems are physically allocated to different spatial sections of the Bobcat, connected by physical interfaces as hydraulic hoses, electrical wires, transmissions belts etc.

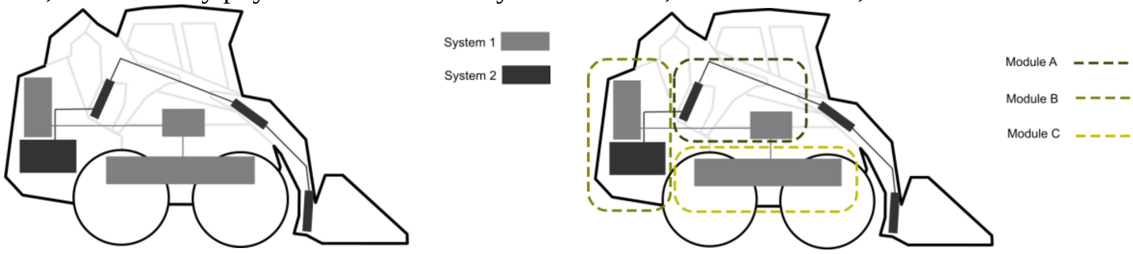


*Figure 2. System structure (left) and a Module structure (right) of a bobcat showing entities belonging to systems and modules and the relations between them*

The second viewpoint, handled in the IFD, is a modular viewpoint in which systems are split and physically joined components are encapsulated into modules. Modules can consist of elements belonging to different systems i.e. developed by different system teams. It is therefore crucial both to integrate systems in modules, but also to handle interfaces created along the module boundaries splitting systems. Figure 2 (Right side) shows the architecture in which the two systems are split in three modules: Base frame module, Engine module, and Hydraulic module. When monitoring the IFD in Visio, it is possible to turn on layers containing specific systems and the interfaces belonging to it. Moreover it is possible to monitor interfaces to other systems. The modelling formalism has been described in prior published work by the authors, but will in short be introduced here. The IFD is modelled by means of blocks and lines in the software program Microsoft Visio. The IFD is normally printed on large blue prints in order to get the overview of the product family it represents. The IFD is used as a boundary object between different developers. Figure 3 is a symbolic representation of an IFD. In order for the reader to quickly understand the structure of the product, it is suitable to model the diagram so the layout is established as a cross section of the actual product. In that way the physical layout of the product is possible to recognise in the diagram. The diagram can be read following the interfaces. For products that process or transforms objects, this gives a logical reading direction, for other products it is up to the reader to find a suitable flow in the model. The main elements of the diagram formalism are objects denoted Interface components (IF components). The purpose of the IF components is to decompose the product family into systems and encapsulate the building blocks into modules. IF components have different characteristics and are modelled in different ways. Each IF component belongs to a product system. To avoid confusion, systems and their interaction must be clearly defined. This is done by choosing the relevant interaction as a basis for determining the system boundary. There is no fixed list of systems to be included in the development. Systems can be modelled and thereby control important properties of the final product. Modules are modelled by arranging IF components inside boxes with a thick black boundary and rounded corners. Modules can contain smaller modules, but they do not overlap as it is clearly defined to which module any element in a product belongs.

The structure of the IFD appears as the relations i.e. interfaces are added to the diagram. An interface, among two IF components, represents a relation, e.g. a physical connection, energy transportation, information flow, or flow of material. The purpose of working with interfaces is to ensure responsibility for the components interaction and to ensure that components are interchangeable, when relevant. An interface between two IF components holds a definition on which is the master and the slave of the interface. This enables a responsible for an IF component to monitor whether he owns the right to change or modify the related interface. There exist a number of interface classes and the list can be extended in order to support the context in which a product belongs. Optional interfaces can be modelled on the diagram to show affected relations between entities or systems if the interface is established.

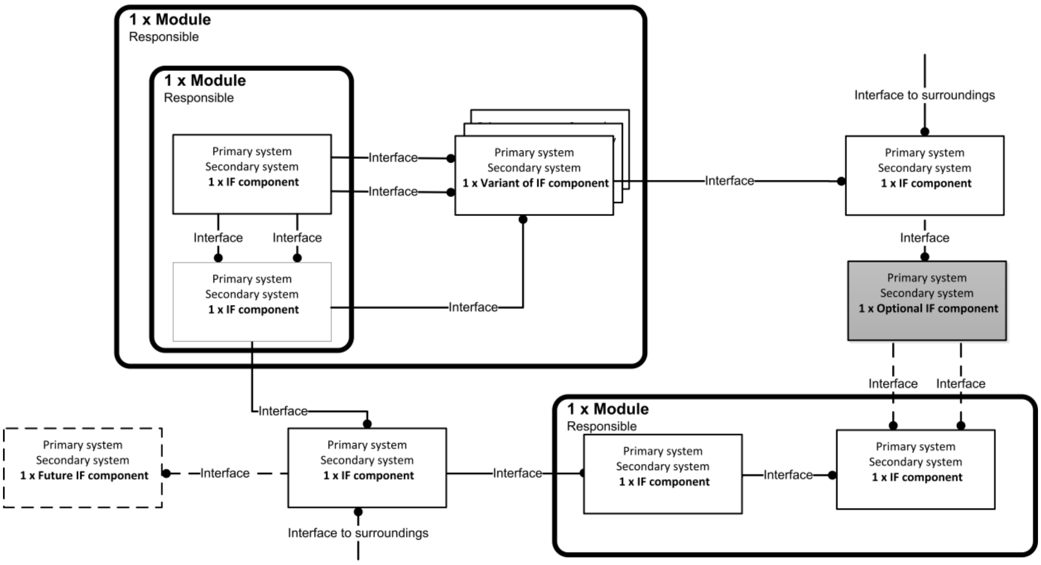


*Figure 3. Symbolic representation of a generic IFD*

## 3.3 PLM support

In this research case, the company's PLM system had features typical for most enterprise PLM systems on the market today (Sääksvuori & Immonen, 2008). The features of the system included: Item management, product structure management, user privilege management, maintenance of the state and status of items, information retrieval, change management, configuration management, workflow management, document management, backup management, history/system log, file vault etc. The PLM system was implemented in parallel with the company's latest product development project, in which the PLM system became the comprehensive source for information belonging to the new product family. The studied company had a great focus on modularisation and standardisation of their products. Because of the complexity of the company's products each containing more than 40.000 unique parts, there was seen potential in developing modules that could be shared by different products. The process of modularisation was handled in many levels in the company, and was supported by a number of methods and tools. By using the IFD from the early design phases and maintaining it during the entire design process, different module concepts could be tested in a fast and simple way. Modularisation supported in the IFD and documented in the PLM system, created some effects that are listed here:

- The definition and development of a product family's system structure: Systems (e.g. cooling or hydraulic) are defined in a bill-of-material seen from a functional point of view. This means that required behavioural properties of a system can be targeted in development, by designing system in their totality. For example can 3D visualisations of the systems be generated in the PLM system, even though they are realised by means of several modules, each containing several system elements.
- The definition and development of a product family's modular structure: Modules are defined in a bill-of-material seen from a modular point of view. A module is created because of different driving forces for modularization, and because a module is composed by components designed by different systems, it is important to design the relations between system and modules, so that the products both fulfill requirements of behavioral properties and requirements to physical realisation in production. 3D visualisations and

reporting of relational properties such as cost and weight of each module, can be created by using PLM system functionalities.

- The definition and development of a product family's interface structure: Interfaces are clearly defined in both a system and a module context. Interfaces can be defined in a structure representing different interface types, and it is clearly defined which components and modules are related to each interface, and which system holds the responsibility of an interface. The template of Interface documents was developed to support the management and the integrity of the modular architecture. Interface documents have the nature of design specifications that can be linked to the interface structure in the PLM system.

For CAD models so called WT parts (Windchill Technology parts) are created automatically when creating CAD objects (assemblies and parts) inside the PLM environment. WT parts are objects that can be linked to upper structures in the PLM system. This is done in order to be able to impose the CAD models according to the chosen structure of interaction (system, module, and interface). Non CAD data is linked to upper structures in the same way as for CAD data. This organises data in a way that is identifiable with the product architecture modelled in the IFD.

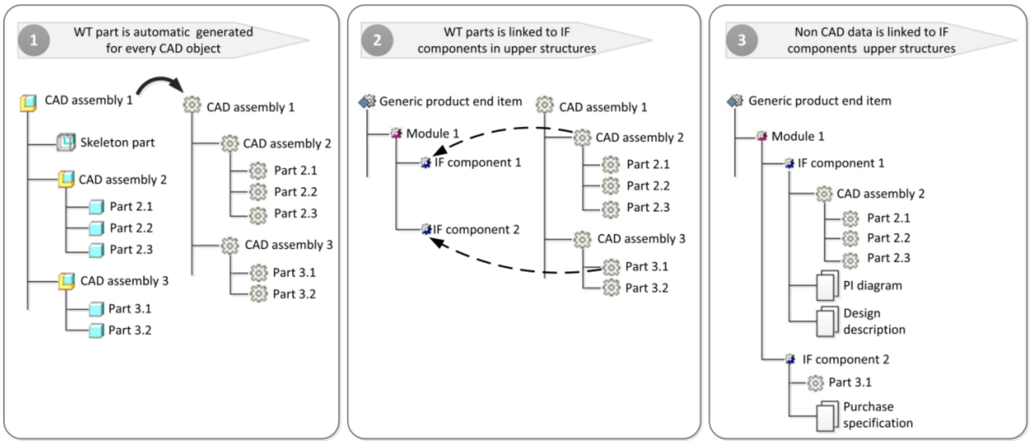


*Figure 4. Data Associativity in the PLM system*

Visualisation of products seen from different perspectives is seen as a strength also in the conceptual phase in order to enhance concurrent engineering, see implications of introducing module boundaries, and in general when focusing on integration of different systems. Figure 5 shows an example from the PLM system in which a module of a front loader and a hydraulic system are loaded in a web-browser. Because CAD models are linked to IF components represented in both a system and a module structure, the CAD models are imposed in proportion to the chosen structure.

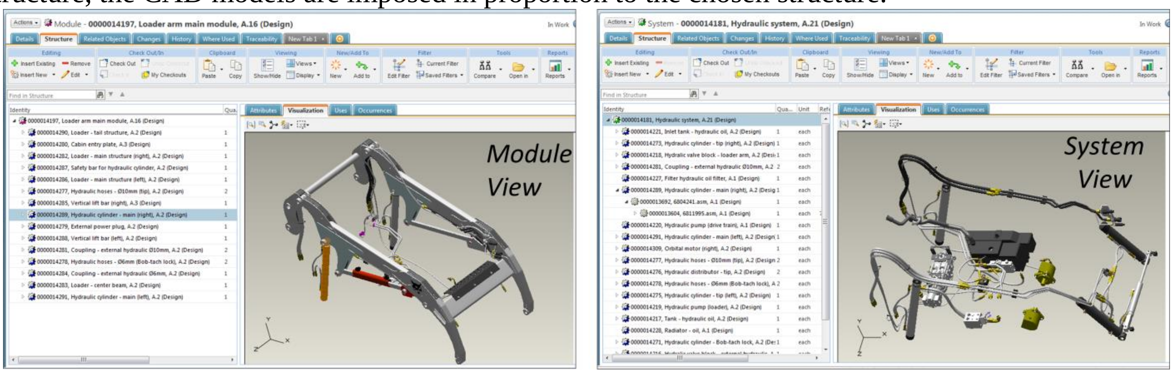


*Figure 5. Visualisation of module and system view*

Reporting capabilities in the PLM system is used to monitor design progress on a weekly basis. The numbers of new, modified, and approved parts are indications on the progress of the design. Furthermore a report on the cost development is generated each week.

Every component in the system is allocated with an initial target cost attribute, and gradually direct cost is added to all components as they are developed or purchased. By means of simple roll up mechanisms cost are added up from the top product level and down to the smallest components. If a cost figure is missing on a component, a target cost steps in. Target cost numbers are provided by financial controllers in collaboration with the relevant developers and purchasers. Cost reporting is in that way a strong tool for supporting a design according to budget, because difference between budget and actual cost is discovered quickly.

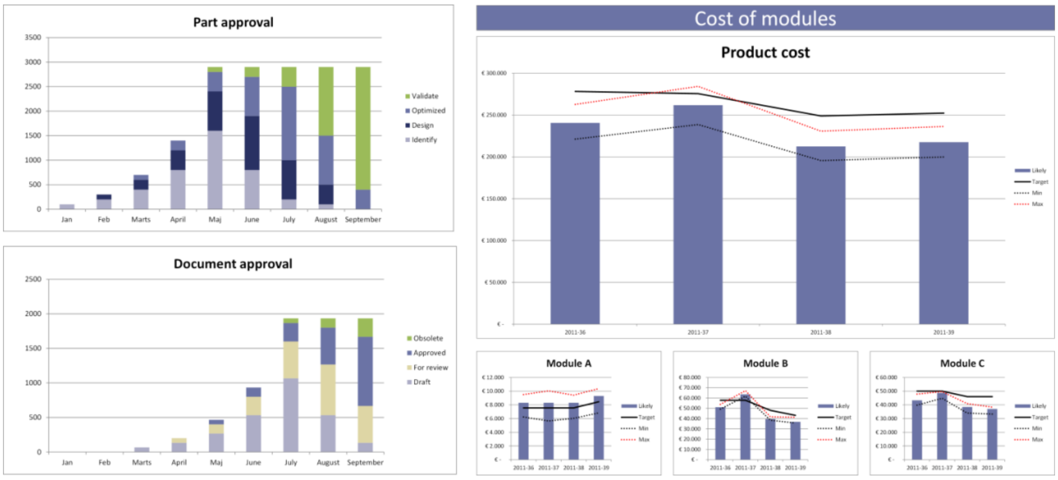


*Figure 6. Example of reports showing design progress and cost development generated from the PLM system on a weekly basis*

## 4. DISCUSSION

This contribution should be regarded as outlining a suggested approach for supporting the activities of developing modular product families. The approach has focus on the abilities in modern PLM systems. The results presented here do not represent a complete framework to describe the development of modular product families, but serve as a contribution of importance to the framework of authors in the area of practical application of supporting tools. A strength in this approach is that it can be used in companies developing products belonging to a diversity of products and industry. Even if strict definitions differ, the fundamental principles of modular design are common: break systems into modules, ensure modules can interchange with each other, and provide well-defined interfaces. Using a visual product architecture model in combination with a PLM system in the design process, support development on a conceptual high level, and still supports management of information on a very detailed level. Support functionalities are: definition of functional system structures, physical module structures, and the interfaces between entities, management of interfaces, and reporting of design progress and cost development. Any products could potentially be modularised and their information could be managed in PLM systems, but to gain more easily benefit from the advantages of PLM systems, companies must be selective in choosing which products to support with this approach. The strength in this approach is its ability to address complex products with a large number of shared components, components belonging to different technology domains, and/or components developed by different organisational teams. To apply this approach for simple products with few components could be categorised as “killing butterflies with muskets”.

## 5. CONCLUSION

This paper has presented an approach for using a visual product architecture model in combination with a PLM system for supporting the activities of developing modular product families. The initial hypothesis has been tested success. The research question has been answered by illustrating the results of the research. One can ask: What is the validity of such a model and an approach? Our proposals shall be meaningful to practitioners, they shall be easy to integrate into their practice and support their reasoning; this is where the validity shall be found. The validity should be found in the feedback through unstructured interviews in the company, reporting the ease of application and the beneficial PLM support in designing modules and maintaining an interface integrity of the product family. The approach is seen as applicable for development of complex products as e.g. members of a product family, with a large number of components, and in less degree as an approach to choose, when developing simple products with few components and simple technology. The approach has been implemented in an industrial setting and the first results by doing this, have been described. The most important results are listed in terms of the experienced effects on the modular design process in the company:

- Clearly defined systems - an enabler for managing the design process and the responsibility within each system.
- Clearly defined modules - an enabler for re-use of modules.
- Clearly defined interfaces - an enabler for re-use of modules.
- More accurate cost reporting because of automated reporting based on modules.
- More accurate design progress reporting because of automated reporting based on modules

The boundaries of this PLM approach are that it focuses on establishing and managing data of modular product architecture. It is an approach that aims at supporting the engineers working on developing modular product structures by managing module documentation and information on interfaces between modules. The approach is not an extensive PLM approach, supporting all stages of a product's lifecycle, e.g. as recycling. Many preconditions and prerequisites exist for successful implementation of modular product architecture based development, which have not been described in detail in this paper. Conditions as e.g. a modern IT-infrastructure, organisational ownership, sufficient resources/competences and high-level anchoring of the initiatives, are all seen as conditions that to some extent have to be in place in companies. Regarding further work, detailing and elaboration of the interface management process could be mentioned, as well as more testing and refinement of the general approach.

## REFERENCES


Abramovici, M. (2007). Future trends in product lifecycle management (PLM). *The Future of Product Development,* , 665-674.

Alemanni, M., Destefanis, F., & Vezzetti, E. (2011). Model-based definition design in the product lifecycle management scenario. *The International Journal of Advanced Manufacturing Technology, 52*(1), 1-14.

Andreasen, M., Hansen, C., & Mortensen, N. H. (1996). The structuring of products and product programmes. *Proceedings of WDK2 1996,* , 4, 28.

Andreasen, M., Mortensen, N., & Harlou, U. (2004). Multi product Development–New models and concepts. *15. Symposium" Design for X", Neukirchen, 2004,* 75-86.

Baldwin, C. Y., & Clark, K. B. (2000). *Design rules, volume 1: The power of modularity* mIt Press.

Bruun, H. P. L., & Mortensen, N. H. (2012a). Modelling and using product architectures in mechatronic product development. *Norddesign 2012, Aalborg, Denmark,*

Bruun, H. P. L., & Mortensen, N. H. (2012b). Visual product architecture modelling for structuring data in a PLM system. *PLM12, Montreal, Canada,*

Ericsson, A., & Erixon, G. (1999). *Controlling design variants modular product platforms*. Dearborn, Michigan: Society of Manufacturing Engineers.

Erixon, G. (1998). *MFD–Modular Function Deployment, A Systematic Method and Procedure for Company Supportive Product Modularisation,*

Harlou, U. (2006). *Developing product families based on architectures contribution to a theory of product families*. Lyngby: Department of Mechanical Engineering, Technical University of Denmark.

Hölttä-Otto, K., & de Weck, O. (2007). Degree of modularity in engineering systems and products with technical and business constraints. *Concurrent Engineering, 15*(2), 113-125.

Krause, D., & Eilmus, S. (2011). Methodical support for the development of modular product families. *The Future of Design Methodology,* , 35.

Manyika, J., et. al. (2011). *Big data: The next frontier for innovation, competition, and productivity.* ().McKinsey Global Institute.

Martin, M. V. V. (2002). Design for variety: Developing standardized and modularized product platform architectures. *Research in Engineering Design, 13*(4), 213-235.

Mikkola, J. H. (2001). Modularity and interface management of product architectures. *Management of Engineering and Technology, 2001. PICMET'01. Portland International Conference On,* 599-609.

Sääksvuori, A., & Immonen, A. (2008). *Product lifecycle management* Springer Verlag.

Stark, J. (2007). *Global product: Strategy, product lifecycle management and the billion customer question* Springer Verlag.
Stark, J. (2011). Product lifecycle management. *Product Lifecycle Management,* , 1-16.
Steward, D. V. (1981). The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management,* (3), 71-74.
Sundgren, N. (2003). Introducing interface management in new product family development. *Journal of Product Innovation Management, 16*(1), 40-51.
Ulrich, K. T., Eppinger, S. D., & Goyal, A. (2011). *Product design and development* Irwin/McGraw-Hill.