Transdisciplinary Lifecycle Analysis of Systems
R. Curran et al. (Eds.)

doi:10.3233/978-1-61499-544-9-165

Implementation and Management of Design Systems for Highly Customized Products – State of Practice and Future Research

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Abstract. Individualized products, resource-smart design and production, and a focus on customer value have been pointed out as three opportunities for Swedish industry to stay competitive on a globalized market. All these three opportunities can be gained by efficient design and manufacture of highly customized products. However, this requires the development and integration of the knowledge-based enabling technologies of the future as pointed out by The European Factories of the Future Research Association (EFFRA). Highly custom engineered products require an exercising of a very rich and diverse knowledge base about the products, their production and the required resources for design and manufacture. The development and implementation of systems for automated design and production preparation of customized products is a significant investment in time and money. However, our experience from industry indicates that significant efforts are required to introduce and align these kinds of systems with existing operations, legacy systems and overall state of practice. In this paper, support for system development in literature has been reviewed in combination with a survey on the state of practice in four companies regarding implementation and management of automated systems for custom engineered products. A gap has been identified and a set of areas for further research are outlined.

Keywords. Customization, Design Automation, Implementation, Management

Introduction

Customization of products is more and more frequently demanded by consumers and OEMs. More time has to be spent on engineering work in order to create the external variety demanded by the market. At the same time competition lowers prices which creates the requirement of high efficiency within product development and production in order to ensure profitability [1]. Fogliatto [2] compares the current utilization of customization with [3], a literature made ten years earlier, and concludes that a clear change have been made in the manufacturing industry towards a higher degree of customization. Rudberg and Wikner [4] divide manufacturing companies in four categories depending on their ability to create customized products. The four categories, starting with the category with lowest possibilities for customization, are: Make-To-Stock (MTS), Assemble-To-Order (ATO), Make-To-Order (MTO) and Engineer-To-Order (ETO). They further put the four categories together with the concept of Customer Order Decoupling Points (CODPs). This is done in order to demonstrate

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where in the product realization process the different company categories receives the customer input in the form of an order (Figure 1). Computer based support systems which enable customization in different degrees have been created and tested in industry. Configuration systems make use of a modular product structure where the modules are combined in the available configuration most suitable for a specific customer [5, 6], and can be seen as the simplest type of system for enabling customization. Then there are systems which enable a higher degree of customization by parametric design [7] and utilization of Knowledge Based Engineering (KBE) [8]. Other systems have been created which are used to automate design as well as simulations for different purposes [9]. Implementing computer support in technology and product development as well as in quotation and order processes have over a time proved to be beneficial for companies' efficiency and productivity.

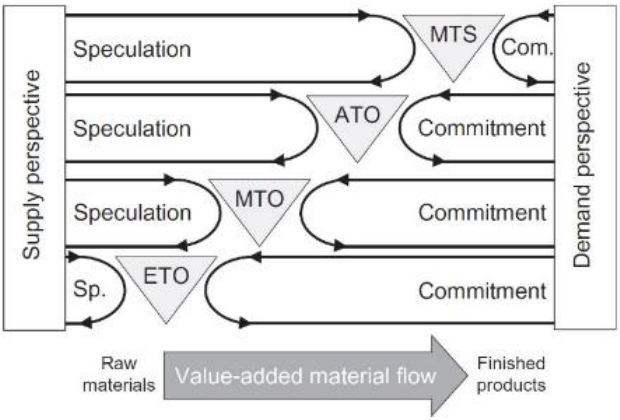

Figure 1. Marks the CODPs for the different company models where larger commitment represents higher possibility for customization [4].

However, to shape either the computer system or the company organization to get the most out of their systems, have been pointed out by industry to be a hard task. Today, a need can be seen for systems which enables increased variety for the market or which are built to adapt products to a specific costumers demand. Cederfeldt and Elgh [10] concludes, from an investigation of 11 SMEs in the Swedish industry, that this need exists from the industry point of view. However, more complex functionality of computer based tools in the engineering work requires a thorough adoption and management strategy. A need can be seen in industry for strategies which enables a more effective use of systems using company knowledge to support product customization. Much research have been focusing on different variations of functionality in the systems in order to fulfill the need of the companies. However, it seems that there is a lack of methods and tools to support implementation and long term management of this kind of systems witch aggravates the companies achieve the fully advantage and profit of their investment. The objective of this work is to outline the current need for research regarding implementation and management of support systems in the engineering design process by investigating existing development methods as well as the current practice in today's industry.

The current state of implementation and management of systems for engineering support in technology and product development have been investigated at four companies. Beside the in-depth survey of industrial practice, existing methodologies for system development in literature has been reviewed regarding their support for implementation and management. The results have been analyzed and discussed for the purpose to outline the knowledge gap which identifies the need of future research. This paper is an initial step in a project active over three years. Within the project this paper can be seen as part of the step “Research Clarification” in the design research methodology [11].

1. Methods and models supporting system development

A method for how to plan a new design automation system is described in [12]. A top down approach starting from specification of system requirement and the problem characteristics is described followed by a mapping to appropriate methods for system realisation. The contribution does not include aspects such as user-friendliness, maintainability or documentation despite the author’s statement that they are of significant importance to success in industrial praxis. Implementation and management issues are argued to be considered only when the fundamentals of the problem have been solved. A set of criteria of system characteristics is defined in [13] including transparency, knowledge accessibility, flexibility, ease of use and longevity. Most likely, these characteristics affect system implementation and management. The criteria are to be considered and weighted in the planning of a design automation system, however, the author state that they do not give concrete answers on implementation and management issues. A procedure for development of design automation systems has been outlined by Rask [14] where issues about documentation and maintenance are addressed by emphasizing the need and importance of routines regarding versioning, verification and traceability. A possible means to support the updating of the knowledge-base is to strive for a design automation system implementation that allows the revision and the documentation to be executed at system runtime [15].

Stokes [16] described a methodology for the development of knowledge based engineering applications called MOKA, Methodology and software tools Oriented to Knowledge Based Engineering Applications. Two central parts of the methodology are the Informal and Formal models. The Informal model is used to document and structure knowledge elicited from experts, handbooks, protocols, literature etc. The Informal model can be regarded as paper-based with text and illustrations. The Formal model is derived from the Informal model with the purpose to model and structure the knowledge in a fashion suitable for system specification and programming. The Formal model is described by an object-oriented annotation called MML (Moka Modelling Language) that is based on UML (Unified Modelling Language). La Rocca et al describe the Design and Engineering Engine, DEE, approach [17-19]. This approach consists of three major elements: The first element is concerned with the design process, which includes multidisciplinary optimisation. The second major element is the Multi-Model Generator (MMG) that uses the product model parameter values in combination with formalised domain knowledge to generate product models. Report Files are generated and fed to the third major element, the detailed analysis modules. These modules calculate the design implications. Finally, the loop is closed by analysing the data files using convergence and evaluation checks. Curran et al [20] extends the DEE approach to the Knowledge Nurture for Optimal Multidisciplinary Analysis and Design, KNOMAD, methodology. The KNOMAD acronym highlights method process of:

(K)nowledge capture; (N)ormalisation; (O)rganisation; (M)odeling; (A)nalysis; and (D)elivery. These implementation steps are taken and repeated as part of the knowledge life cycle and in this context, KNOMAD nurtures the whole Knowledge Management across that life cycle. Further, this method includes an approach for multidisciplinary design (optimization) and for knowledge capture, formalization, delivery and life cycle nurture. Despite the methods described above and the numerous KBE applications developed and describe in scientific publications, a number of issues to be research still exists. This is supported by an extensive literature review by Verhagen et al [21] where the major shortcomings of KBE have been outlined.

Hvam et al [5] describes a complete and detailed methodology for constructing configuration systems in industrial and service companies. They suggest an iterative process including the activities: analysis of product portfolio, object-oriented modelling, object-oriented design and programming, among others. Every activity results in a description of the problem domain with different levels of abstraction and formalisation. The analysis of product portfolio results in a Product Variant Master (PVM) and Class Relationship Collaboration (CRC) cards. The maintenance is proposed to be organised by introducing Model managers. The Model managers are responsible for the delegation, coordination, collection and documentation of domain expert knowledge. This documentation is then used by the programmers to update the system. Haug et al [22] have developed a prototype system for the documentation of configuration systems that is founded on one data model. This documentation system is separated from the implemented product configuration system. Documentation is in both cases above considered as an important enabler for efficient maintenance. Claesson [6] have introduced and developed the concept of configurable components. The concept includes a function-means model to provide design rational for the encapsulated design solutions which could support the understanding of the system and thereby support system implementation and maintenance – this is, however, not surveyed.

During implementation, limitations are set of how the system can be used in the future as well as how it can be maintained/updated over time. Bermell-Garcia [23] proposes a method directed to KBE which aims to facilitate management of applications by increasing transparency and traceability by the utilization of Enterprise Knowledge Resources (EKRs). This method however considers the systems at a low level of granularity with whole KBE applications as elements in a knowledge base and does not explain how the applications or the system for creating the applications should be developed in order to be transparent and enable traceability. In [24], case studies within KBE has been investigated and five problems regarding long-term use of KBE application were identified:

- Poor application modeling causes knowledge loss.
- Flaws in development language causes knowledge loss.
- Application development for wrong reasons causes knowledge misuse.
- Low amount of standardization in applications causes high maintenance costs.
- Full potential of the knowledge are not used due to problems in sharing and re-use of knowledge.

From the reviewed literature it can be concluded that relevance is seen in further elaboration of development methodologies to consider the area of implementation and management of engineering support systems. More specifically, factors which are thought to be affecting this are related to system transparency, traceability of knowledge and modelling of knowledge.

2. Industrial practice at the companies

The companies subject for the in-depth survey acts in different areas of the market and are of varying size from a few hundred up to 8000 employees. All companies work according to the model Engineer-To-Order (ETO). A short description of each company follows.

Company 1 is a global actor in the area of development, production, service and maintenance of components for aircraft, rocket and gas turbine engines with high technology content. Company 1 provides products that are completely custom engineered in an internationally market with high competition. The products are integrated in complex systems working in extreme environments for long time periods with both customer and legal demands for complete documentation and traceability. The company takes full responsibility for the functionality of their products during its operation including service, maintenance and updates. Fulfilling these harsh requirements is a challenge but at the same time an opportunity to sustain a competitive edge. Automation of design and production preparation by the use of knowledge based engineering (KBE) has been used at the company for more than a decade to enable quick adaptation to changes in customer specifications and evaluation of different design solutions.

Company 2 is the world's leading supplier of tools, tooling solutions and know-how to the metalworking industry. Company 2 is active in an internationally very competitive market and needs to constantly cut development lead time by seeking means to improve their processes and system maintenance. The company has a long standing tradition in automation of quotation and order processes and has adopted an engineer-to-order business model supported by systems for automated design and production preparation of customized product. A request for quotation of a custom engineered product is replied within 24 hours including detailed design drawings and a final price. All the necessary documents and manufacturing programs are automatically generated when the bid is accepted by the customer.

Company 3 is a global manufacturer of a wide assortment of products for transporting equipment by car, including roof racks, bike and water sport carriers and roof boxes. Company 3 sees an opportunity to considerably cut time and cost in their development and manufacture of roof racks for cars by the implementation of a system for the customization of rack attachments to new car models. Every car model requires an individual adapted attachment consisting of a footpad and bracket and currently there exist more than 400 footpads and 1100 brackets. To be able to quickly launch a roof rack for a new model is considered as very important as it is common that a roof rack with accessories to be mounted on the rack is included as additional equipment when a new car is bought.

Company 4 is a worldwide supplier of insert stapling units for copiers, printers and document handling systems. Company 4 has recently been incorporated under a larger brand given the directives to focus and strengthen their position as a worldwide supplier of insert stapling units for copiers, printers and document handling systems. The insert stapling units is developed and manufactured on contract with different OEMs. Every unit model has to be adapted to the system it will be an integrated part of. A product platform has been defined to cut product cost and development lead time. The platform is based on a modular product architecture to be configured for the different OEM's individual specification. However, the platform covers only a limited part of the product design and additional custom engineered parts have to be added.

Activities directed towards formalization and structuring of knowledge in applications supporting the engineering of these parts have been taken by individuals but they are not shared on a corporate level.

The industrial practice at these companies is presented within four areas.

2.1. Implementation of commercial and in-house developed systems

It could be concluded that none of the companies which participated in the investigation utilizes any pre-described model or guidelines in order to handle implementation of new computer based support systems. The approach for handling implementations are decided for each individual case and no information was found regarding consideration of lessons learned from earlier implementations. Because of this it is more likely that problems will re-occur in different implementation projects. The company closest to having a formalized method is Company 1 which, for larger implementations, assigns an organization change manager. They are also testing all new systems on test servers before it is released in live operation. This might not always save time in the implementation process but it can save costs by detecting errors before anything have been produced with the system. Company 2 which develops a lot of similar applications could benefit by having a more standardized proactive thinking regarding implementation as well as management during development of the applications. This can also be reflected in research claiming that low standardization of such applications causes knowledge loss [21]. The creation of their own programming language can be seen as a step towards a more standardized structure of the code in new applications. Company 3 and 4 perform all implementation completely case-based.

2.2. Management of commercial and in-house developed systems

None of the companies have a proactive approach to management and maintenance of the systems. They all perform maintenance when new needs or problems are identified. Over all transparency of the development processes is something Company 1 wishes to keep high. The transparency in an individual support system however is usually low since there are no focus on that. The organization have trust in the process assurance of all systems which are implemented. By having a low level of transparency in systems and applications, the company cuts the connection between the produced material and the knowledge which was used in the system or application. If errors occur in a product or if an engineer wishes to re-use knowledge, the low traceability followed by the low transparency could result in time and/or knowledge waste. If defective knowledge cannot be traced, it can continue to produce errors or lowered quality in future products. This lack of transparency could create obstacles for people trying to perform maintenance of the systems since it could be hard to find out what has to be done. Over all the management of systems in Company 1 can be seen as structured compared to the other companies due to the reason that they do have some specified steps of which to follow. Company 2, 3, and 4 have not adopted any structured guidelines of how to perform their maintenance. In Company 3 and 4 it is not seen as a big problem but Company 2 which makes use of a larger amount of applications, and also performs more maintenance work to their systems, could benefit from a more systematic method to address this aspect.

2.3. System connection to produced material

A problem which have been noticed during the interviews in all companies, however most applicable to Company 1, was the lack of documenting information about system version and knowledge document version to produced material. Since both the systems and the knowledge documents are affecting the project output in different degrees, it is seen as relevant to save information of this connection. This is seen as important in order to ensure that an error can be traced to the knowledge which created it. Company 2 do not document connections between produced material and systems which affects the outcome of the product. This puts Company 2 in the same situation as described for Company 1 above. Company 3 and 4 have no need for this topic.

2.4. Knowledge re-use

It can clearly be seen that Company 1 to a large extent are able to re-use knowledge created in technology development to be used within product development. A problem which was discovered in Company 1 is that no common terminology is used when creating the documents containing the knowledge. This have caused some issues regarding searching for specific knowledge documents. The low amount of knowledge re-use in Company 2 is thought to be a result caused by low standardization in the formalization of knowledge created by the design engineers. Report files content varies a lot from engineer to engineer and it is not certain that the Company can make use of them in new projects. A more standardized way to formalize this knowledge could result in a higher re-use of the knowledge which could both save time and ensure quality of the produced products. Company 3 are able to re-use knowledge if there exists a finished project with output which satisfy new requirements. If there are no matching case, they cannot make use of any formalized knowledge. In order to get Company 4 to start re-using knowledge (CAD models are possible to re-use) they would have to adopt a knowledge formalization model, suitable for the type of knowledge stored, which enables engineers to easily find a CAD model which could be used for a new set of requirements.

3. Knowledge gap and future research

As can be concluded from the review of supporting methods and models, extensive research and development have been devoted to technical aspects of building systems for specific products, and some research have been directed towards general methods and models supporting system development, although, little attention has been paid on the actual implementation and management of systems in operations. The experience from industry indicates that significant efforts are required to introduce and align these kinds of systems with existing operation, legacy systems and overall state of practice. System management including adapting existing systems to changes in product technology, new product knowledge, production practices, new customers and so forth is also challenging. Research in design automation and knowledge based engineering has not focused on implementation and management issues in industrial operation. The aspects are pointed out as important but merely treated as consequences of other actions without studying the actual need, trade-offs in development and supporting methods and tools required. Verhagen et al [21] has based on an literature review outlined shortcomings of KBE. Four of these that could have an impact on implementation and management are: system transparency, knowledge sourcing and re-use, semantics of knowledge models and traceability. However, the review is not supported by any survey in industry. Concerning configuration system, documentation has been pointed out as important for maintenance issues and different models and tools exist to be used as support. The main principles are interesting and are most likely applicable to some degree, however, there is no evidence that the specific methods and tools can support a generative product model in an automated engineer-to-order business model.

There is currently a difference in the extent of usage both of computer support in the engineering design as well as formalized methods in how to implement and manage systems in the investigated companies. Since there is a difference in this utilization between the companies, they express the need of methods with varying scope. Two main problems were identified in Company 1. The first problem regards the knowledge flow between different domains. The way of formalizing the knowledge in one domain is not always suitable for another. Here a need of a knowledge formalization model, which facilitates multi-domain utilization are seen. The other problem regards traceability of knowledge. A finished product can be traced back to the systems used to create it. However, there are no documentation of which version of the systems used to create this specific product. This means that if the knowledge used in the systems is changed, the knowledge used to create the product in focus cannot be found. For Company 2 the main problem lies within the use of knowledge created by the design engineers. Programmers are supposed to use this knowledge to create design automation applications but the low standardization in how this knowledge is formalized frequently creates obstacles in their work. They also have a low re-use of knowledge created in old projects which is believed to be a result of the method used to formalize and store knowledge. The current need in the smaller companies, Company 3 and 4 which more rarely implements new systems in their organizations, are seen in a more general method which can help the companies to more effectively introduce new systems in their live operation.

The need for support and further research can be summarized in three areas: **(1)** Models which enables companies to formalize their knowledge to facilitate multi-domain utilization: The lack of methods which aids engineers to formalize their derived knowledge in a way to make it understandable to people in other domains, which might be the users of the knowledge, have proven to be a reason to communication inefficiency. A need is seen for the creation of guidelines or models of which to follow when formalizing knowledge which is to be of multi-domain utilization. This is seen as relevant in order to enable engineers communicate their knowledge in a way which enables a diversity of knowledge interpreters. **(2)** Documentation of relations between produced products specific system versions, used in the products creation, in order to connect it to the knowledge of which it was derived from: Increasing the possibilities to find knowledge, which once have been created or stored within a company, could lead to higher transparency and thereby decrease knowledge loss by facilitated maintenance. The transparency could be gained by creating and maintaining connections between product instances, system version, and knowledge version. **(3)** Guidelines for introducing design support systems in an existing process: Smaller companies with little experience of system implementations might not find it profitable to apply an extensive methodology. Here a need is seen for more general guidelines of which to follow in order to obtain a successful implementation while keeping the aspect of maintenance during use in mind.

The Companies in the study are seen as representable for both the industrial frontier in utilization of engineering support systems as well as for companies with less experience in the field. While Company 4 might be considered as somewhat behind the average company regarding utilization of engineering support systems, Company 1 would be representing the frontier with a large number of academic employees which performs work and research in related areas, especially KBE. The company is well aware of existing methods but cannot find the desired support in them for their activities. Company 2 is also far ahead of the average company with an in-house developed programming language adapted for creating design automation applications and long experience within the area. Company 3 are seen as ahead but closer to the average company in its utilization of engineering support systems. A few systems exists within the company but they are new in the area with a low amount of experience.

4. Conclusions

Over all it can be concluded that some of the companies, especially Company 1, have adopted structured methods in order to handle implementation and management of their systems as well as documentation of knowledge derived from technology and product development. However, in all companies a need for methods of how to handle implementation and management in order to make a more effective use of their systems can be seen. A set of areas relevant for further research have been identified which are thought to affect this. In general, literature conforms to these and the need for further research are strengthened by the confirmation of their industrial relevance. Future work will focus on the development of methods, supporting implementation and management of engineering support systems by consideration of the identified research gaps, through further investigations at the companies. Success criteria will be derived and case studies will be defined and executed at the participating companies.

5. Acknowledgment

The authors would like to express gratitude towards the participating companies in the study as well as The Knowledge Foundation who partly funds the project.

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