Reuse of manufacturing experience
in product and process definitions

Petter Andersson
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Petter Andersson

Division of Functional Product Development
Department of Applied Physics and Mechanical Engineering
Luleå University of Technology
Thesis

This thesis comprises an introductory part and the following appended papers:

**Paper A**
*Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective*

**Paper B**
*Manufacturing system to support design concept and reuse of manufacturing experience*

**Paper C**
*Manufacturing experience in a design context enabled by a service oriented PLM architecture*

**Related publications**
The following published papers are related to the thesis but not included:

*Knowledge Enabled Pre-processing for structural analysis*

*Automated CFD blade design within a CAD system*
Petter Andersson, Malin Ludvigson and Ola Isaksson, Proceedings of the Nordic seminars, Integration of computational fluid dynamics into the product development process, National Agency for Finite Element Methods and Standards, Gothenburg, November 2-3, 2006
Abstract

Today’s manufacturing industry faces hard competition, both in the form of competitor’s low cost outsourcing and to reduce labour cost. Increased public consciousness for environmental pollution and stricter government legislation are also drivers for a more efficient product development process and companies competing on the global market must continue to improve there methods and tools to gain an advantage. The company’s intellectual properties and the ability to capitalize on experience from earlier projects becomes a key factor when competing on the global market. This thesis work explores the mechanisms for knowledge reuse and suggests methods and tools involved in the product development process to improve the use of manufacturing experience in order to prevent manufacturing flaws to reoccur in new product development programs.

The research is carried out in a project funded by the Swedish research agency VINNOVA together with the industry, through the MERA program. The project aims to improve the Digitally Linked Process and has a focus on Experience reuse. An initial research question was formulated to address the problem and guide the research towards a better understanding; “How can experience from manufacturing processes be tied and reused to impact the definition of governing product and process definition?”

A study was set up to investigate the current practices and to aid the research in formulating an approach to improve methods and tools for Reuse of Manufacturing Experience (RoME). The study was conducted at two companies, one in the aerospace industry and one in the automobile industry. The “How” and “Why” questions supported a case study approach. The study provided a better understanding of the problem and pointed at a number of opportunities to increase the use of manufacturing experience. One of the findings pointed out in the survey was the lack of a working process for preventing recurrence of a bad design in manufacturing. Furthermore, the study revealed a potential improvement in the use of capability data and problem reports that are captured and stored in databases, today more or less solely used in manufacturing. A new research question was formulized as the improvement of the RoME process where set in focus;

“How can the process of experience reuse from manufacturing phases be improved to better impact earlier phases in product development?”

The current process for finding and accessing process capability data from a Design Engineering perspective were investigated and described as well as the process to retrieve problem report notifications regarding specific design features of a component. The process where found to be both time consuming and tedious, and as a result of that, seldom used by design engineers.

Key enablers having a significant impact on the RoME process where identified.

- The ability to find and access experience captured in the manufacturing phase.
- The ability to provide data in a context familiar for the receiver in order to facilitate the learning process.

An improved process for reuse of manufacturing experience is proposed and includes methods and techniques to target system integration for search and access. A service oriented product life cycle management (PLM) architecture is proposed as a mean to address the topic of finding and accessing manufacturing data. The standard for PLM
Services 2.0 provided by the Object Management Group (OMG) and the increased maturity of web service technology provide the possibility to integrate knowledge rich engineering application in a dispersed heterogeneous system environment.

The ability to provide data in a context that is familiar to the receiver is addressed by developing a web based graphical user interface (GUI). The web based GUI presents the manufacturing data in a design context where manufacturing process capability data and problem report notifications are presented in a component view. This supports the design engineer when searching for relevant experience from earlier projects by associating the process capability data and problem reports to a specific design feature, e.g. a flange, and how it relate to the manufacturing process.

A web based application is developed to demonstrate the concept. The application presents the product assembly (bill of material) together with the manufacturing process activities and corresponding process capability data in the same view, providing a contextual environment that is tailored for the receiver.

**Key words:**
Acknowledgement

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1 Introduction

1.1 Background

Globalization and increased competitiveness call for improvements in all Product Life Cycle phases across disciplines. Life cycle dependency does not only include the “product” itself but also accompanying services, such as maintenance and repair, customer training etc. The term used for products, having a service contend, is called “Functional Product” (Alonso-Rasgado, 2004). The service integration in manufacturing challenges the competences, roles and responsibilities of manufacturing companies (Tan 2007). One of the critical life cycle phases decisive for how to design the product is obviously the manufacturability. Hence, this work focuses on methods and tools to improve engineering processes within the manufacturing industry.

The manufacturing process is a major cost driver in the product life cycle and competition from low cost areas in the world has amplified the importance to move from a resource based manufacturing model to a knowledge based model where the resources are used as efficient as possible (Manufuture, 2004). Public environmental concern and government legislation are also drivers that force the industry to improve the development processes. Increased life cycle responsibility includes environmental sustainability. As formulated in a report from ACARE, the Advisory Council for Aeronautics Research in Europe, that comprises of about 40 member states;

“The industry must rise to this challenge and confront the competitive pressures imposed on it both by the rapid development of globalization and environmental needs. Since this process is also fuelling such a strong growth in passenger demand that air traffic will triple over the next 20 years, the Group's vision has had to encompass the air transport system and not just the manufacture of aircraft and equipment” (ACARE, 2001)

A company’s intellectual property is one of the key assets when competing on the global market, hence the ability to capitalize on experience from earlier projects becomes increasingly important.

Technology advancement in Virtual Product Development and Virtual Manufacturing enable both the product and the corresponding manufacturing process to be described in computer models. It is evident that the logical sequence appearing in the physical world (i.e. a product need to be manufactured, before any manufacturing testing can be conducted) is not true anymore. The product definition and associated manufacturing process can be defined in a more simultaneous way then ever before.

In new aircraft engine programs there is no longer time to iterate alternatives where hardware (consuming lead time) is a limiting activity. The capability to define the entire product realization process virtually is practically already here and large R&D efforts are now focusing on making the virtual process robust. This virtual approach is not traditional and lacks of experience, something which is crucial in aerospace manufacturing industry. This is a rationale for research in the area and a motivation for this research.

Development of design systems of today are rapidly evolving and facing an increased multidisciplinary integration challenge. Knowledge Based Engineering and the use of standard and formal procedures are considered important steps towards the vision
where design requirements on an abstract functional level have a direct impact in the conceptual selection process.

Design for manufacturing, DFM, and design for assembly, DFA, aims to ensure that manufacturability is taken in account in the design process. Methods and tools in this area provide support to simulate the manufacturing process and to provide the designer with guidelines for design solutions.

1.2 Reuse of manufacturing experience

It is recognized that experience from earlier and ongoing projects is a great asset for a company in the competition on the global market. Learning from earlier projects provides the company means to stay ahead and benefit from new solutions and new ideas without getting into the same pitfalls as earlier “new ideas” have experienced. The best way to treat non-conformances and flaws in manufacturing is to simply avoid them.

1.2.1 Methods and tools for experience reuse

Cost, Cost avoidance, Quality, Control, shortened lead time and robustness are some of the criteria’s that are identified as drivers for product development and also used to evaluate different design concepts. Hence, methods and tools are developed to improve product development within these areas, e.g. Six Sigma, Cost optimization, Manufacturing Simulation, Design for Manufacturing and Design for Assembly. The ability to capitalize on the company knowledge and experience from earlier projects becomes a key issue in the development and improvement within these areas.

Today, the improvements within the manufacturing industry mainly focused on manufacturing processes and methods within the manufacturing area, trying to shorten lead-time on the machinery floor. Feedback for design improvements are manually delivered when asked for, usually during a design meeting or a design review (Andersson, 2008a).

To better meet the requirements of the industry today, new and improved ways are needed to close the gap between the manufacturing floor and the design process (CoBDM, 2004).

Making use of manufacturing experience in the development of new products as well as improvements of existing products can be viewed in several different perspectives. One perspective is from an organizational view where the focus is now to involve experienced users from earlier projects in new projects. Another perspective is the company’s operational management view where the process of how experience that appear in manufacturing is to be fed back in the product development process.

Methods and tools for retrieving data are approached within the area of data mining (Wang, 2007), where both the ability to search and access existing data are recognized as well as methods for storing data with additional meta information to support the search process.

New repositories of information used in product development are knowledge sharing tools like Content Management Systems, CMS, wikis, web-forums, and the use of personas (Grudin, 2002). These sources facilitate sharing of experience among a community of users.
Knowledge Based Engineering, KBE, technology is used to capture engineering knowledge and to aid the engineer in the design process (Stokes 2001). By utilizing manufacturing experience in the capturing process, manufacturing aspects are included in the KBE tool or model (Boart, 2006b).

1.3 Aim and Scope
The aim of the research presented in this thesis is to improve manufacturability and avoid reoccurrence of design flaws in new projects. The approach is to gain a better understanding of the mechanisms for reuse of manufacturing experience and improve the feedback of manufacturing experience from the manufacturing phase back to earlier phases in the products life cycle.

The scope of this research project is enclosed within the DLP-E project and includes the development of generic models for how data of experience from ongoing production can be integrated in the development of new or improved products.

It is recognized that the earlier aspects of manufacturability can be introduced the higher impact on production readiness can be addressed. Experiences and techniques existing in the domain of Knowledge Based Engineering are used as an initial approach to capture, formalize and realize experiences from manufacturing processes.

1.4 Initial Research Question
The initial research question stated in the project:

“How can experience from manufacturing processes be identified and reused to impact the definition of governing product and process definition?”

1.4.1 Technical and commercial aspects
The technical aspect is closely related to product development engineering with:
Improved capability for finding and accessing manufacturing experience as well as improved support for multidisciplinary design.

The commercial aspect of my work is to reduce product life cycle cost and enable a more robust design offer for the customer.
1.5 Research environment

This research has been funded by the DLP-E project within the MERA (MERA) program, a VINNOVA (VINNOVA) initiative. I am a member of the Functional Product Development department at Luleå University of Technology and the work has been carried out in collaboration with Volvo Aero and the Production Technology Centre, PTC, Innovatum in Trollhättan, Sweden. Parts of the research have been carried out at SAAB Automobile in Trollhättan, Sweden. The Volvo Group KBE network cluster has provided financial and steering support.

1.5.1 MERA and the DLP-E project

Manufacturing Engineering Research Area, (MERA) is a package of more than 40 three year R&D projects with a budget on approximately 600 MSEK. Of these are 305 MSEK funded by VINNOVA, Nutek (Nutek) and Västra Götalandsregionen (VG). The rest of the funds are provided by the companies. There are approximately 60 companies and 40 research groups engaged in the MERA program. During the development of the MERA program an inventory of the industrial need where performed, both for long term and short term.

Program main areas
- Manufacturing processes
- Production systems
- Virtual and digital support

Four domains where defined in relation to at least two of the three main areas identified above. These domains are;

I. Specific manufacturing processes and integrated production development.

II. Development and operation of manufacturing processes with virtual and digital support.

III. Control, verification, optimization of equipment and liner with virtual and digital support (including the DLP-E project).

IV. Strategies, principles and methods for manufacturing; concept development.

DLP-E, Digitalt Länkad Processstyrning med Erfarenhetsåterföring, Swedish definition for; “Digitally Linked Process control with Experience reuse”. DLP-E is a MERA project in the third domain, Control, verification optimization of equipment and liner with virtual and digital support. The project contributes to the MERA
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Program aim to increase the knowledge based production in Sweden, partly by the efforts in research and that the project is based on knowledge fusion.

The DLP-E project is expected to deliver generic models for how data of experience from ongoing production can be integrated in the development of new or improved products. The DLP-E project is also expected to verify the efficiency of these methods through verification in practice of three different products with a different level of complexity. In addition, the DLP-E is assumed to affect the systems and methods captured into commercial software. This is accomplished by the active participation of software vendors.

Reused data from manufacturing is to be processed statistical and be visualized on a 3D CAD model for easy communication. Improvements are verified by both function and performance as well as in comparison to other manufacturing processes in knowledge based system solutions for future product development with the aim to provide cost efficient production processes. A production based PDM system is to be used as base for the experience reuse.

It is concluded that the project will deliver methods and tools for:

- Manufacturing preparation and product design based on process capability
- Manufacturing preparation based on experience

1.5.2 Volvo Aero

Volvo Aero is part of the global company Volvo Group, which at 2007 had a turnover of 285 billion SEK and more than 100 000 employees. Volvo Aero itself had a turnover of 7,646 million SEK and approx. 3200 employees in Trollhättan and Linköping in Sweden, Kongsberg in Norway and Boca Raton, Newington and Kent in the United States of America. The company is specialized on developing and producing large structural components of commercial jet engines. The company also develops products for the European space program Ariane and has military product development programs mainly for the Swedish department of defense.

Volvo Aero has 5 adjunct professors, 40 employees with a PhD degree and the company hosts approximately 15 PhD students.
1.5.3 Luleå University of Technology

Luleå University of Technology is the most northern located university in Sweden and it has research with close ties to industry and a holistic perspective. This work has been carried out within the Division of Functional Product Development (FPD), one of 12 divisions at the department of Applied Physics and Mechanical Engineering.

1.6 Disposition of the thesis

This thesis is assembled by an introductory part, research approach and a summery of three contributing publications. The three appended publications presents the current industrial practices for re-use of manufacturing experience and key mechanisms to support the process of transferring experience from the manufacturing phase as well as a proposal to improve the process of experience feedback.

Chapter 1 is the introduction including background, aim of the research and a short description of the environment where the research has been carried out.

Chapter 2 presents the research approach.

Chapter 3 describes the frame of reference with the area of relevance.

Chapter 4 summarizes the appended papers.

Chapter 5 gives a description of the work and presents the findings.

Chapter 6 includes conclusion and discussion.

Chapter 7 suggests future work.

Chapter 8 includes references in this thesis.
2 Research approach
To understand the feedback mechanisms of manufacturing experience it is necessary to understand the current practices for re-use of manufacturing experience.

2.1 Design research
Design research aims to formulate and validate models and theories about design phenomena as well as develop and validate knowledge, methods and tools - founded on these models and theories. In addition, design research also aims to improve the design process (i.e. support industry producing successful products). In this context, my work focus mainly on improving the process for reusing manufacturing experience by understanding what current practices and tools exists and how they are used. Figure 2, the design research as described by Blessing et. al in the paper “What is this thing called Engineering design” (2002)

Figure 2. Design research, adopted from Blessing (2002).

2.2 Design research methodology
Figure 3 outlines the basic design research methodology proposed by Blessing (2002) describes four stages, research clarification, descriptive study 1, prescriptive study and descriptive study 2. This is an iterative process that involves observation & analysis, assumptions & experience as well as observation & analysis.
The first part of this work is to identify the overall goal of the research. Here are the criteria for success identified with the aims that the research project is expected to fulfill along with the focus of the research project, the main research questions and/or hypotheses. Here are also the measurable criteria identified, difficulties with measurable criteria’s for design research has been discussed by Eckert et al, (2004), pointing out the need to integrate different types of research, many of which are aimed at increasing understanding, and only very indirectly at achieving improvements.

Descriptive study part 1 identifies the factors that influence the formulated criteria, how they influence these and how they relate. The reference model of influencing factor is developed. This stage provide a basis for the development of support to improve design and provide more details that can be used to evaluate development design support.

The Prescriptive study involves the development of an impact model or theory describing the expected improved situation based on the results of the first descriptive study and assumptions. Support of a prototype or demonstrator is developed in a systematic way and evaluated with respect to its in-built functionality, consistency, etc.

Descriptive study 2 identifies whether the support can be used in the situation for which it is intended and whether it does address the factors it is supposed to address. It is identified whether the support contributes to success, addressing usefulness, implications and side effects.
2.3 Problem formulation

Figure 4 below illustrates the stakeholders and the information flow that where described as an initial view of the problem. What methods and tools can be provided in order to facilitate feedback of manufacturing data to engineers located in earlier phases of the product life cycle process? How can a learning process be ensured that prevents mistakes from earlier projects to recur in ongoing or future projects?

In more detail, the short feedback loop goes from manufacturing operations back to the production system and can be a fully automated process where NC programs are adjusted based on sensor signals integrated in the machine by an adaptive control system. Experiences here are quite close to data patterns, and local in character. The context is far from the designer’s context. The feedback of information from manufacturing operations back to manufacturing engineering effects decisions regarding production flow, tools and machines. The manufacturing engineer has a role in managing experiences in this phase. Knowledge about manufacturing impact of design decisions made by the design engineer has a high impact on the PD life-cycle and therefore a possible greater impact on product cost. Production feedback to design and manufacturing preparation in the CAD environment is still limited and usually a process of updating embedded rules. If successful, the embedded rules directly in the design tools can be quite powerful whereas the process of doing so may be sensitive and difficult to keep updated.

In the initial study of current industrial practices for re-use of manufacturing experience, two types of experience feedback where identified. **Push** and **Pull**. “Push”
is where the information appears somewhere in the product lifecycle, e.g. a fault in the machining process and the incident is to be considered important and need to be sent to other stakeholder, see Figure 5. The process of converting lessons learned into best practices could be seen as pushing the content of lessons learned from one project to the next.

![Figure 5. Push information from the process to other stakeholders in the product life cycle.](image)

The other type of information feedback is through pull, where the information is requested, e.g. the design engineer is requesting capability and performance data of a process.

The study revealed several areas for improvements concerning experience feedback. As described in the paper (Anderson 2008a), a vast amount of documentation is stored in databases and project areas and the re-use of this information is limited.

The study provided a better understanding of the problem and pointed at a number of opportunities to increase the use of manufacturing experience. One of the weak spots pointed out in the survey was the lack of a working process for preventing recurrence of a bad design in manufacturing. The study also revealed potential improvement in the use of capability data as well as problem reports captured and stored in databases, today more or less solely used in manufacturing.

In the DLP-E project it is stated that data is to be statistically analysed and visualized in a 3D CAD model to enable easy communication between the users, hence the focus was set to improve the usability of existing data in two critical sources, the database for process capability analysis and the database for problem report notifications. A new research question was formulized as the improvement of the RoME process where set in focus.

### 2.3.1 Research question
As the process was identified as a problem a new research question was formulated to give a better focus as;

“How can the process of experience reuse from manufacturing phases be improved to have a greater impact in earlier phases of Product Development?”
3 Frame of reference
This chapter explains the area of contribution and outlines the influencing factors relevant to manufacturing experience reuse.

3.1 Areas of relevance and contribution
Figure 6 presents areas that are relevant when reusing manufacturing experience and where this work contributes.

3.1.1 Knowledge
The definition of knowledge has been argued long before it was used in design engineering, for example characterized by the ancient Greek Plato as “justified true belief”. The meaning of the word “knowledge” is described differently depending on the context where it is used, in Oxfords Advanced Learner’s dictionary (Cowie, 1989), the term Knowledge is in the form of understanding, “A baby has no knowledge of good and evil” or “I have only limited knowledge of computers”. In MOKA, Methodologies for Knowledge Based Engineering Applications, the term knowledge is briefly described as information in context (Stokes 2006). In the field of Knowledge Management, knowledge is often put in a hierarchy form of a pyramid where data is based at the bottom and in context becomes information, see Figure 7. Then information that is interpreted enables a person to gain knowledge. Adding experience and you have wisdom, and at the top there is sometimes the truth. (Jashapara, 2004), (VIVACE).
Knowledge exists only in the human mind and can then be regarded as *tacit* knowledge or *explicit* knowledge, where tacit knowledge is the kind of knowledge that is difficult to express, things that you know, but are not shore why. In contrary, explicit knowledge is the knowledge that you are able to communicate with others.

In this work, the pyramid model is used to point at the importance of providing data in a context that is logically presented for the receiver of the information to better support a learning process. Also, knowledge from one user has to go through some other media, speech, text, visualization etc., and be interpreted by a receiver to enable the learning process between to people.

In addition the pyramid model highlights the need to turn tacit knowledge into explicit knowledge to facilitate transfer of knowledge.

### 3.1.2 Manage Engineering Knowledge

One of the key issues in an engineering project today is to keep track of, secure and share information content.

Knowledge Management, KM, is increasingly influencing the academic and industrial research as shown in Yinian Gu bibliometric analysis of global knowledge management research (Gu, 2004) where he found that the distribution of articles is rather widespread - they published in 462 titles of serials, spanning 110 Journal Citation Reports subject categories. Showing the diversity of KM as mixture that has just recently starting to become its own field. KM is also described as a “process by which individual learning and experience is accessed, reflected upon, shared, and used to foster enhanced individual knowledge and organizational value” (Coleman, 1998). As the complexity of KBE models increase with the number of parameters and engineering disciplines involved the need to develop formalized KM and KBE tools and strategies becomes clear (Terpenny 2001)
Professor Ikujiro Nonaka, who is frequently quoted and referenced in publications discussing knowledge management, describes the knowledge creation as “spiraling” process of interactions between explicit and tacit knowledge (Nonaka, 2000). The interactions between the explicit and tacit knowledge lead to the creation of new knowledge and the combination of the two categories makes it possible to conceptualize four conversion patterns.

Nonaka put forward different “Ba's” which facilitate the knowledge conversion for his SECI Knowledge creation model. The four conversion patterns of knowledge are illustrated in the table below, going from Socialization to Externalization followed by Combination and then to Internalization:

<table>
<thead>
<tr>
<th>Tacit Knowledge</th>
<th>Explicit Knowledge</th>
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<tr>
<td>Tacit Knowledge</td>
<td>Tacit Knowledge</td>
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<tr>
<td>Tacit Knowledge</td>
<td>Explicit Knowledge</td>
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<tr>
<td>Explicit Knowledge</td>
<td>Tacit Knowledge</td>
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<tr>
<td>Explicit Knowledge</td>
<td>Explicit Knowledge</td>
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</tbody>
</table>

Figure 8. Nonaka's SECI Model.

In the paper “From Information Processing to Knowledge Creation: A Paradigm Shift in Business Management” (Nonaka 1996), information technology can act as a mean to help implement the concept of “the knowledge-creating company”.

Dave Snowden, Director of IBM’s Institute for Knowledge, suggest in his paper “Complex Acts of Knowing: Paradox and Descriptive Self-awareness” (Snowden, 2002) that we are now reaching the end of the second generation of knowledge management, with its focus on tacit-explicit knowledge conversion and that the third generation requires the clear separation of context, narrative and content management and challenges the orthodoxy of scientific management.

A. Candlot, et al (2006), gives an example where MOKA (MOKA), is used to formalize the link between Design and manufacturing to sustain the resulting knowledge base during the system lifecycle.

J.C. Aurich and Z. Gu (2006) presents another approach that is a concept of knowledge based active design of the physical manufacturing. Applicable methods are developed for the modularization of manufacturing engineering knowledge and systemization of this knowledge to be knowledge cells, so that the new conceptual framework of designing physical manufacturing systems can be implemented. They also introduce a comprehensive knowledge management cycle in order to support the effective and efficient dealing with manufacturing engineering knowledge.
Wiki’s

A webwiki is a group collaboration software tool based on web server technology where the user can add, edit, remove and sometimes configure the content. The use of this type of knowledge sharing is increasing as the web publishing tools are becoming more accessible for non advanced programmers. One of the key functions provided is the built in version control system, providing the ability to roll back from a

Examples of this are; A wiki at the “Geometric and Intelligent Computing Laboratory” (Drexel University) and “The Tabletop Machine Wiki” (Tabletop Machine Shop) - A division of Linss Industries, LLC, or the Virtual Organization for Innovation in Conceptual Engineering Design.

Wikipedia (Wikipedia) has to be mentioned since it is a large example of “Global knowledge sharing” with an impressive 2,532,350 articles in English alone (26th August 2008) and even more in a number of different languages. "Wiki" (/ˈwɪki/) is originally a Hawaiian word for "fast" and the Encyclopedia is constantly growing since anyone can log in and add or edit the pages. The fact that anyone can edit or add false information has not stopped people from using it and it is often used a source to find links to reliable information and sometimes referenced as the source of information. The “vandalism” of this encyclopedia seems to be little and is usually caught by another editor.

Forums

Forum, newsgroups or Blogs are web tools frequently used on internet communities as a mean to raise a question or start a discussion (phpBB). Questions and answers are viewed and discussed by several users supporting the sharing of both the problem and answer in a topic. Another effect of sharing a discussion among several community members is similar as in real life project meetings, the members comes closer to a common view or consensus of a subject.

3.1.3 Knowledge Based Engineering

Knowledge Based Engineering, KBE, as defined in the book “Managing Engineering Knowledge” edited by Melody Stokes; (2001) “The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way”.

This is a wide definition of KBE and traditionally KBE systems differs from ordinary CAD systems with some key functions in the functional programming languages that provide an advantage. One is that it utilizes lazy evaluation to accomplish a demand driven geometry engine, enabling an efficient update process of the geometry definition (AML), (COE kbe bp). Combined with a dynamically instantiated class structure with support for object oriented features such as inheritance the systems provide a flexible and efficient way to handle a variety of concepts, which is especially appreciated in the early phases of a product development project.

KBE’s ability is to capture and reuse engineering knowledge has been used in CAE areas (William 1998), (Aganovic 2002), (Andersson 2006), (Boart 2006a) and can also be viewed as an object oriented modeling technique where knowledge is captured into the product model using “knowledge objects”. A “knowledge object” is a formal and/or informal description of design intent, that, when applied on the product model restraints the configuration and limits the solution space.
KBE has been found useful with the ability to constrain geometry to abstract objects, (e.g. cost objects, manufacturing objects and organization objects) with rules and databases. A challenge with this approach is that the system tends to expand and become wide ranging, beyond possibility to survey. Therefore, the program architecture defining relations and rules has to be well structured and easy to maintain.

The software architecture of a program is the structure, which comprises software components, the externally visible properties of those components, and the relationships among them (Len 1998). Computer programs have a tendency to grow and parametric dependencies to tangle across the class structure. Object Oriented Programming is one way of dealing with this problem. Object-orientation is a technology based on objects and classes. It represents a methodological framework for software engineering and its pragmatics provides for a systematic engineering discipline. However, as Oscar Nierstrasz (1989) puts it, "Object-oriented languages and systems are a developing technology. There can be no agreement on the set of features and mechanisms that belong in an object-oriented language since the paradigm is far too general to be tied down. We can expect to see new ideas in object-oriented systems for many years to come.”

The ability to capture engineering knowledge using KBE technology enables reuse of experience as the KBE model is updated based on data from the manufacturing process.

### 3.1.4 Robust Engineering - Six Sigma

Although Six Sigma can be viewed as a part of DFX in the sense of Design and Process improvements it deserves its own headline and this brief explanation. Six Sigma is a method that has mainly been applied for manufacturing processes but is also used in other areas such as engineering design, referred as “Design for Six Sigma” (Watson, 2005). The method emphasis on a top down commitment in the organization and are based on a hierarchy management model which reflects the roles from top to bottom as ; Champion, Master black belt, Black belt, Green Belt and White belt. Six Sigma describes quantitatively how a process is performing. To achieve Six Sigma, a process must not produce more than 3.4 defects per million opportunities. A Six Sigma defect is defined as anything outside of customer specifications and a Six Sigma opportunity is then the total quantity of chances for a defect (Magnusson, 2003).

Two methodologies practiced in Six Sigma are; DMAIC, an improvement methodology used for process improvements (mainly manufacturing processes) and DMADV, an improvement methodology used for design improvements. The basic methodology of DMAIC consists of the five stages; Define, Measure, Analyze, Improve and Control. DMADV is similar but consists of the five stages; Define, Measure, Analyze, Design and Verify.

According to Watson (2005), DMADV methodology should be used instead of the DMAIC methodology, when:

A product or process is not in existence at your company and one needs to be developed.

The existing product or process exists and has been optimized (using either DMAIC or not) and still doesn't meet the level of customer specification or six sigma level.
The methods and tools developed for Six Sigma aims to reduce the errors by improving the engineering processes both in the production phase as well as in the earlier design phase. The ability to feedback data from earlier project supports the Six Sigma methodology in the different stages of DMAIC/DMADV.

3.1.5 Engineering process improvements
As mentioned earlier in this paper, KBE methods and technology have been used to not just shorten one engineering activity but also the engineering process by automating the interfaces between different activities in a process. Two examples of this approach are exemplified in Boart 2006a and Andersson 2006.

3.1.6 Functional product development
Functional product development is primarily dedicated concept development, where the development of hardware components and services meet in a global, distributed business oriented process. The focus is set on knowledge based, information driven and simulation support in a life cycle perspective to enable the design of a total offer.

If the traditional focus has been to define a product based, mainly on a functional requirements perspective - a Functional Product perspective highlights the need to account for knowledge from all life cycle phases.
4 Summery of appended papers

This chapter summarizes the appended papers and explains their contribution to this thesis.

“Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective”


The publication presents the main findings from a study of two companies where the current practices for reuse of manufacturing experience were explored. The study aimed to investigate the information exchange between three organizational roles; the design engineer, manufacturing engineer, and the production technician, in four phases of the product development life cycle. Current practice of methods and tools where explored and analyzed.

The publication contributes to this thesis by providing a better understanding of the current practices for re-use of manufacturing experience in the industry.
P. Andersson, *Reuse of manufacturing experience in product and process definitions*

"Manufacturing system to support design concept and reuse of manufacturing experience"


The publication focuses on key mechanisms to support the process of transferring experience from the manufacturing phase back to earlier phases in the product's life cycle, e.g. Manufacturing Preparation and Design Engineering, and highlights the challenge of understanding data from a different field.

The publication contributes to this thesis by describing the current process for capturing process capability data from a design engineering perspective as well as the process to retrieve problem report notifications regarding specific design features of a component. Key enablers that have a significant impact on the RoME process where identified.
“Manufacturing experience in a design context enabled by a service oriented PLM architecture”


The publication addresses key enablers for efficient reuse of manufacturing experience identified in the previous publication. A solution is suggested that includes a PLM architecture to enable an efficient way to find and access the data and a web based GUI is described to present the data in a user context.

The publication contributes to this thesis by suggesting an approach to improve the use of existing manufacturing experience by implementing web based graphical user interface that integrate existing data sources using a service oriented PLM architecture.
5 Reuse of manufacturing experience in product and process definitions

This chapter provides a summary of the research work and findings that has been carried out as part of the project.

In addition to Figure 4 that illustrates the stakeholders and information flow, Figure 9 displays four life cycle phases and the contextual dimensions of three organizational roles, manufacturing operations, manufacturing engineers and design engineers. The vertical arrow illustrates the challenge of transferring experience from earlier projects to ongoing and future projects.

5.1 Case study at two manufacturing companies

To explore the current situation a case study was performed in two large manufacturing companies, each with co-located engineering resources. One of the companies studied was an aeronautical engine components manufacturer, and the other one was an automotive manufacturer.

The aeronautical company has a strong history in manufacturing of aeronautical engine components and has recently increased the effort to undertake both development and production of these components. The aeronautical company collaborates tightly with several different OEM’s as a supplier risk and revenue sharing partner.

The automotive has a long history of developing cars as an OEM. Over the last 15 years the company has successively developed from an independent manufacturer to a company within a large automotive enterprise. The range of experience obviously covers both development and production of their products over a long time.
The scope of the study and the means and resources available for the data collection indicated that three sources of evidence were suitable: interviews, questionnaires and written comments. Interviews, covering a rich and in-depth data collection enables a flexible way to sense what is important and focus on that issue. Questionnaire survey with multiple choice questions and in addition to these, written comments. The Questionnaire where written in the respondents native language, Swedish.

Three organizational roles, Design Engineering, Manufacturing Engineering and Manufacturing Operations, were asked to fill in the questionnaire. 30 respondents within each of the disciplines at both companies ended up with 180 forms to analyze. The questionnaires were distributed to the participants and filled in at a meeting were the authors where present. On some occasions the questionnaires were distributed by e-mail. The questionnaire survey was performed prior to the interviews and both the questions and the preliminary result from the survey was used as a basis for discussions in the interviews.

The questionnaire survey was uniquely designed for each organisational role, design engineer, manufacturing engineer, manufacturing operations with approximately 25 questions in each questionnaire.

5.2 Findings from the case study

Data from the interviews, questionnaire survey and associated comments were analyzed using techniques described in Miles & Huberman (Miles 1994). The collected information was arranged in different areas with a matrix of categories.

5.2.1 Perceived frequency of recurring problems

The perceived frequency of reoccurring issues in manufacturing was explored to indicate the effectiveness of an existing process for reuse of manufacturing experience. The response of the survey showed that it was common with recurring problems, although the frequency of them was perceived differently among the respondents.

The awareness of a working process for reuse of manufacturing experience was found to be poor at both companies, although 61% of respondents in the automotive company stated that there are processes to prevent designs that have caused problems in manufacturing from recurring, however only 8% of those thought that the processes worked. The aeronautical company showed a quite different result, with only 11% of respondents thinking that there was a process, and out of those 44% thought that the process worked.

These results reflect that there were more outspoken processes in the automotive company, although the use of the processes was unsatisfactory.
5.2.2 Manufacturing competence in early phases of PD

The perceived involvement in early phases of design was studied since cross disciplinary teams have been showed to be effective as a feedback mechanism.

The survey revealed that manufacturing operations have a low level of involvement in the conceptual phase in both companies. Manufacturing engineers perceived involvement in the conceptual phase where significantly better for the automotive company (45%) but still poor for the aeronautical company (10%). The perceived involvement from design engineers where higher (75% aeronautical, 82% automotive), although not all design engineers participates in the concept phase.

The three most frequently used means of communication were identified in the survey as: telephone calls, e-mail and small meetings. Surprisingly low was the use of IT-tools for sharing desktop information; less then 5% of the engineers have indicated this tool as one of there 5 most common mean for communication.

5.2.3 Systems for manufacturing experience

Both companies have developed support systems for capturing and providing experience from earlier projects into new projects, although the automotive company has a richer flora of tools, possible as a result of being an OEM in a larger organization working with similar products. Here databases are used to store “Lessons learned” documentation from all company sites.

Similar to the automotive company, there is a vast collection of measuring data from manufacturing that goes many years back. This data is only used by manufacturing today, although the information would help design engineers to know more about the current manufacturing capabilities.

5.3 Find and access manufacturing experience

The obvious approach is to store the information so that it becomes easier to find in future projects. To address this issue, meta data is often used to add key words to documents in order to categorize the data and position it in a context. However, it is not always the case that you know what you are looking for in future projects so there is a need to be able to search for various data in an unstructured data source. This problem is approached using tools for data mining that take advantage of advanced algorithms to explore the content of a data source (Wang 2007).

5.4 Contextualization of manufacturing experience

The ability to find and access data in various databases is alone not enough to ensure that the experience from earlier projects is used in ongoing and upcoming projects. It is equally important to understand the view of the receiver in the feedback loop and the engineering environment that surrounds him. How does the “element of experience” on the atomic level relate to his view? In a more detailed example, how do we make the design engineer understand the meaning of statistical data presented from an individual milling operation? The result could be highly dependent on previous operations and the status of that machine at that particular time. To what type of geometry topology is data related to? What project?
Design engineers need to understand how the experience data in manufacturing relates in the context of engineering design. Figure 10 describes the feedback loop in a design to manufacturing context. Where an Element of Manufacturing Experience, EME, in this case a statistic report of characteristics are presented in:

a) The context of component structure.
b) The associated manufacturing process.
c) The process activity, the milling operation.

In order to support the engineer in his task to find and understand past experience the involved systems need to build on the designer’s context and provide the ability to interactively search, find and retrieve data in a heterogeneous system environment as the related information is dispersed in several different sources. To be able to react in ongoing projects it is necessary that information provided in the support tool is up to date and built on data from other ongoing projects.

The current process for searching and retrieving process capability data and problem reports were explored and analysed, the process was found to be both tedious and time consuming since it included several steps and involved going into different systems databases in a manually manner.
5.5 Manufacturing experience in a design context enabled by a service oriented PLM architecture

The requirements presented in Andersson (2008b) are addressed in the third publication appended to this thesis (Catic 2008). Figure 11 describes the relation between the different data sources, service layer for integration and the design context.

A solution is presented that includes a PLM architecture to enable an efficient way to integrate a dispersed system environment and to find and access data in real time. The standard for PLM Services 2.0 provided by the Object Management Group (OMG) and the increased maturity of web service technology provide the possibility to integrate knowledge rich engineering application in a heterogeneous system environment.

Figure 11. Relation between data, service layer, design context and presentation.
P. Andersson, *Reuse of manufacturing experience in product and process definitions*

A web based GUI is proposed to address the need to present data in a context tailored for the receiver. Manufacturing process capability data and problem report notifications are presented in a component view. This supports the design engineer when searching for relevant experience from earlier projects by associating the process capability data and problem reports to a specific design feature, e.g. a flange, and how it relate to the corresponding manufacturing process.

Figure 12 present a web based application that has been developed to demonstrate the concept and provide a better understanding of the needs and requirements discussed in this work.

![Figure 12. Designers graphical user interface for search and understand manufacturing experience.](image)

The layout includes data from several sources presented on one page, providing the engineer information in a design context.

Visible features in the graphical presentation are; project filter, enabling the engineer to choose previous projects. A component breakdown displays the assembly structure of the product and by choosing a subcomponent, the corresponding list of operations reveal the manufacturing process. In addition to this, quality notifications generated by an activity in the process is displayed and easy to access.

Initial work for implementation in an industrial environment is ongoing as a part of the VINNOVA funded project.
6 Discussion & conclusion

The initial question “How can experience from manufacturing processes be identified and reused to impact the definition of governing product and process definition?” was approached by conducting a case study at two companies to investigate the current practices for Reuse of Manufacturing Experience, RoME. The case study provided a better understanding of the problem and revealed several opportunities to improve methods and tools for reuse of manufacturing experience.

Findings from the case study indicated an insufficient process for preventing recurrence of a bad design in manufacturing. In addition, the study showed that the use of process capability data and problem reports captured and stored in databases, is today more or less solely used in manufacturing and not utilised in earlier design phases. A new research question was formulized as the improvement of the RoME process where set in focus;

“How can the process of experience reuse from manufacturing phases be improved to better impact earlier phases in product development?”

The current process for capturing process capability data from a design engineering perspective were investigated and described as well as the process to retrieve problem report notifications regarding specific design features of a component. The process was found to be both time consuming and tedious, and as a result of that, seldom used by design engineers.

Key enablers having a significant impact on the RoME process where identified.

- The ability to find and access experience captured in the manufacturing phase.
- The ability to provide data in a context familiar for the receiver to facilitate the learning process.

An improved process for reuse of manufacturing experience was proposed and includes methods and techniques to target system integration for search and access. A service oriented product life cycle management, PLM, architecture was presented as a mean to address the topic of finding and accessing manufacturing data. The standard for PLM Services 2.0 provided by the Object Management Group (OMG) and the increased maturity of web service technology provide the possibility to integrate knowledge rich engineering applications in a dispersed heterogeneous system environment.

The second issue where addressed by developing a web based GUI to present the data in design context where process capability data and problem report notifications are presented in a component view. This enables the design engineer to search for relevant information of a component feature from earlier projects.

The approach presented in this chapter has a potential to reduce the time necessary to find and access experience in the included database from hours to almost an instance. The proposed solution would also enhance the designer’s ability to understand the information as it is tailored for a designer’s context.

Furthermore, the support for the designer in these systems can be of different types, both automatically executed rules and functions executed in a parametric model, as well as provide the designer the right information at the right time to aid in his decision.
The ability to capture engineering knowledge in a design system opens up new possibilities to make use of experience databases. By feeding a knowledge based design system with experience that are captured from different phases of a product's life cycle, design rules and decisions executed in the design system are based on this experience.

### 6.1 Future work

Future work includes a final implementation of the proposed solution followed by a validation of the result.

This could be approached by separating the challenges discussed in this paper, finding & accessing manufacturing data and present the data in a context that is logical to the receiver.

The first challenge involves system integration and is highly dependent on resources in the industrial IT environment. The second challenge deals with graphical presentation and the logical presentation of data from a dispersed system environment.

Both issues are important and needs to be solved in order to increase the use of manufacturing experience.

#### 6.1.1 Drawing centered definition to computer model centered

In this work, the emphasis has been to improve the usage of experience data already collected in databases. To improve the ability to search and trace the coupling between statistically process capability data and requirements set by the design engineer further development of the process is needed. Today, vital information is “hidden” in drawings and impossible or difficult to extract. There is a need to fully “digitalize” the content and move from a drawing centered definition to a computer model centered definition.

#### 6.1.2 How to use the feedback?

There are several possibilities to facilitate the manufacturing experience feedback, e.g. include experienced personal in new projects, include experienced personal in the education process as well as update best practice, instructions or other regulating documentation based on experience from manufacturing. Or, as proposed in this thesis, improve the process for finding and accessing data collected in the manufacturing process.

Data from experience can be used to validate processes, methods, instructions or tools. The quality of a manufacturing process simulation is measured by how close it is to reality. Hence, the simulation algorithms are updated and improved by feeding back data from manufacturing experience. The same argumentation yields for methods, instructions, tools etc. In order to facilitate such a feedback loop there is a necessity to keep track of which instruction/method/tool where utilized for a particular measured result.

Hence, a continuation of this work is to explore the different scenarios for experience feedback further to enhance the use of manufacturing experience in a company.
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Paper A
Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective

Paper B
Manufacturing system to support design concept and reuse of manufacturing experience

Paper C
Manufacturing experience in a design context enabled by a service oriented PLM architecture
Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective

P. Andersson, A. Wolgast and O. Isaksson

Keywords: Product development, Manufacturing experience, Best practice, Experience Management

1. Introduction

The impact on manufacturability due to decisions made during Product Development is well known and approaches such as Concurrent Engineering (CE) and Design for Manufacturing and Assembly (DFMA) [Boothroyd 2002], [Egan 1997], have been used for some time. Despite the significant efforts made in academia and within industry - experiences gained during production tend to remain within the manufacturing organization leaving the opportunities for increased product manufacturability and potential for cost reductions untapped. For that reason, this paper aim to investigate current practices for reuse of manufacturing experience with the objective to identify the best practice and effectiveness of re-use mechanisms. More explicitly, this paper investigates the perceived effectiveness of capturing and feedback mechanisms from manufacturing and production to the design phase.

Two companies are studied, Company A, which is an Aeronautical Engine Components manufacturer, and Company B, which is an Automotive manufacturer. Company A has a strong history in manufacturing of aeronautical Engine Components and has recently increased the effort to undertake both development and production of these components. Company A collaborates tightly with several different OEM’s as a supplier risk and revenue sharing partner. Company B has a long history of developing cars as an OEM. Over the last 15 years the company has successively developed from an independent manufacturer to a company within a large automotive enterprise. The range of experience obviously covers both development and production of their products over a long time.

In this paper re-use of manufacturing experience addresses how experience found in the production work is made available and eventually used during design of a next generation product (see figure 1).
As seen in figure 1, transferring and using experience from manufacturing in design by definition require a multi disciplinary perspective and is a matter that challenges the learning capability of the organization. How to achieve a learning organization has been a topic for decades [Argyris 1996], [Mulholland 2005]. Still, the question remains whether or not industrial best practice has significantly improved? In the best of worlds the learning organization should already be implemented. In practice however, most industries of scale struggle with recurrence of manufacturing issues.

This study has studied three organizational roles

- The design engineer, who works in the context of product definition
- The manufacturing engineer, who works in the context of manufacturing process definition, and
- The Production technician, who works in the context of (serial) production of the physical artifact.

Four of the product life cycle phases are here covered by the concept phase, the detailed design phase, manufacturing preparation phase and the serial production phase, see fig. 1.

There are different approaches to deal with the topic “reuse manufacturing experience”, covering areas such as data mining [Wang 2007], information sharing, and organizational learning. The knowledge management cycle comprises a range of activities used to discover, generating, evaluating, sharing and leveraging knowledge [Jashapara 2004], [Awad 2003], and is therefore closely related to this topic when it comes to managing experience captured in the manufacturing process. The process of capturing knowledge for reuse of project knowledge has been studied by Tan et al and Kamara et al [Tan 2007], [Kamara 2003], where the focus is set to capturing the experience live in a project. Learning situations identified by Tan et al include weekly site meetings, project reviews conducted at the end of each of the project stages, post project reviews, etc.

One mechanism to facilitate experience from manufacturing in design is to work tightly together in product development. This is at least partly the reason to work in multidisciplinary teams following methodologies such as Integrated Product Development [Andreasen 1987] and Concurrent Engineering [Kusiak 1993]. Learning from other disciplines is here enabled since experienced
engineers are working tightly together. The effort to make design changes in the early design phases is far less then introducing the same design change in later phases. In combination with the known impact on success factors (Cost, quality and timing) by early design decisions, the early design phase remains a highly interesting phase to improve [Fleischer 1997]. Thomke and Fujimoto [Thomke 2000] highlights two approaches in order to reduce recurring problems; project to project transfer of knowledge and rapid problem solving. Cross-disciplinary teams are consequently a mechanism for re-use of experience.

Methods and techniques for learning from earlier projects within the same phase are done trough both human to human contact, e.g. personal rotation [Kane et al 2005] and non human transfer by utilizing instructions and system support such as databases of earlier projects experiences [Alizon 2006].

What type of knowledge that is important for the engineer has in an industrial case study been identified in order to ensure appropriate training and competence [Ahmed 2007]. Here, Conceptual design, Value improvements and Detailed design where among the three most important types of knowledge. Tan et al [Tan 2007] has categorized KM tools for capturing and sharing knowledge tool as KM techniques (non IT tools) and KM technologies (IT tools). Post-project reviews, communication of practice, forum and training where he identified as KM techniques and Groupware, documentation of knowledge, expert directory and custom-design software where identified as KM technologies.

The classical challenge of re-using experience from manufacturing can be investigated by:
1. Measuring the recurrence of manufacturing problems over product generations.
2. Investigating the involvement of different disciplines during early phases in design, in the spirit of concurrent engineering and integrated product development
3. Surveying what processes and tools are used for manufacturing experience feedback and their perceived effectiveness.

2. Research methodology
The aim of this study was to describe the current situation in the area of reusing manufacturing experience and to explore what ideas that exist to improve the conditions; hence the “How” and “Why” questions support a case study approach [Yin 2003].

2.1. Case study
Due to the scope of this study, the means and resources available for the data collection, both interviews and questionnaires were used. Interviews, covering a rich and in depth data collection enables a flexible way to sense what is important and focus on that issue, and questionnaires, with multiple choice questions and in addition to these, written comments. Data from the interviews, questionnaire survey and associated comments were analyzed using techniques described in Miles & Huberman [Miles 1994]. The collected information was arranged in different areas with a matrix of categories.

2.2. Survey
Three organizational roles, Design Engineering, Manufacturing Engineering and Manufacturing Operations, see fig. 1, were asked to fill in the questionnaire. 30 respondents within each of the disciplines ended up with 180 forms to analyze. The questionnaires were distributed to the participants and filled in at a meeting were the authors where present. On some occasions the questionnaires were distributed by e-mail. The questionnaire survey was performed prior to the interviews and both the questions and the preliminary result from the survey was used as a basis for discussions in the interviews.

2.3. Interviews
The interviewees were selected on the basis of their profession and position in the company. There were three design engineers and one manufacturing engineer from aerospace and two manufacturing engineers from the automotive industry.

3. Case study findings

3.1. Perceived frequency of recurring problems

Ideally, once a failure or non-conformance is discovered in production, there should be a process that assures that the issue is solved and that experience gained is feed to designers to avoid such failure mode to re-occur. As a first indicator of effectiveness of such process, the perceived frequency of reoccurring issues in manufacturing was studied amongst the three study groups.

The diagram in fig. 2 presents the perceived frequency of recurring problems in manufacturing that the respondents experience in their work. The data originates from rating-scales used in the questionnaire, where the position to the very left was defined as ‘never’ and to the very right as ‘every project’. Each point in the diagram shows the rating from a specific respondent belonging to either Design Engineering, Manufacturing Engineering or Manufacturing Operations, from now on referred to as ‘DE’, ‘ME’ or ‘MO’ respectively. The diagram shows that it is common with recurring problems, although the frequency of them is perceived quite differently among the respondents.

Figure 2. Perceived frequency of recurring problems

Comments in the questionnaire varied between departments; respondents from manufacturing operations gave concrete examples of components that they have been struggling with over the years, whereas respondents from design and manufacturing engineering commented on difficulties with making compromises that where acceptable for all. As a design engineer comments on the question about recurring issues: “It is usually a result of different compromises where some function had to give way for another.” Results show that in company B recurring problems were regarded as more frequent among employees in manufacturing operations than among employees in manufacturing engineering and design engineering. The result in company A is quite the opposite, where manufacturing operations tended to perceive the recurrences less frequent than manufacturing and design engineers.

The questionnaire reveals that 61% of respondents in company B state that there are processes to prevent designs that have caused problems in manufacturing from recurring, however only 8% of those think that the processes work. 26% of the respondents did not know if there was a process and the remaining 14% stated that there were no such processes. Company A show a quite different result, with only 11% of respondents thinking that there is a process, and out of those 44% thought that the
process was used. 76% of respondents did not know if there was a process for this and 13% thought that there was no process. These results reflect that there are more outspoken processes in the automotive company, although the use of the processes was unsatisfactory.

3.2. Manufacturing competence in the early phases of product development

As a second indicator of effectiveness of the experience re-use, the perceived involvement in early phases of design is studied since cross disciplinary teams have been showed to be effective as a feedback mechanism. Manufacturing experience from earlier projects is usually made available through the composition of new design teams where competence from the manufacturing disciplines is included. Respondents in the survey where asked to indicate their involvement in all four phases, concept, detailed design, manufacturing engineering and serial production. Figure 3 shows the percentage of respondents that believe that they have a higher involvement than “little” or “none”.

Manufacturing operations have a low level of involvement in the conceptual phase in both companies. A significant difference between the companies is shown for manufacturing engineers; a little more than 10% of company A engineers recognize they are involved in the conceptual phase whereas more than 45% of company B manufacturing engineers feel they are involved in the conceptual design. The study also makes known that not all design engineers participates in the conceptual phase. Comments to this question reveal that there is a will to have more influence from manufacturing in the concept phase and that globalization effects e.g. that the production is not local, is perceived to have a negative effect on the influence from manufacturing in early phases, which are consistent findings in the two companies. It should be noted that in Company B are the roles of Manufacturing Engineering and Design Engineering are organized in the same business organization, whereas in company A, Manufacturing Engineering and Manufacturing Operation are organized in the same business organization.

In addition to the study of involvement in early phases, the perceived contact between design engineers and manufacturing engineers was explored. Respondents from design engineering were in this case asked to answer to how frequently they are in contact with manufacturing engineers in the different product development phases and manufacturing engineers were asked the same question about design engineers. Fig. 4 illustrates the percentage of daily or weekly contact and the result reveals a difference between company A and company B. The difference in perceived contact is significant between the design engineer and manufacturing engineer in company A in early phases.
Figure 4. Design and manufacturing engineers perceived contact.

The three most frequently used means of communication were identified in the survey as: telephone calls, e-mail and small meetings. Surprisingly low was the use of IT-tools for sharing desktop information; less then 5% of the engineers have indicated this tool as one of there 5 most common mean for communication.

3.3. Systems for manufacturing experience

Finally, the process and systems support for feedback of manufacturing experience has been investigated since existence and use of such systems are often emphasised in company initiatives to improve feedback of experience and make information available for later work. Several systems for feedback coexist in both companies and there are also different ways of using them. In company B there are global databases where specific lessons learned documents and best practices are stored; however there are not that many entries from the Swedish site. Lessons learned can also be an activity at the beginning and end of a project where experiences are documented during a five-hour session, resulting in a report covering the issues, countermeasures and introduction dates. Manufacturing operations have another lessons learned system that is used for sharing good ideas about industrial engineering among the factories in Europe, see Fig 1. Experience reports are used in parallel with the new systems across the organization and are either continuously updated or created at project endings. Another source of documented experience from manufacturing is a database with statistics from an in-line system in the plant that collects measurement data from every vehicle that is produced of a specific model.

**Table 1. Survey of tools available for use of manufacturing experience**

<table>
<thead>
<tr>
<th>Company A</th>
<th>Company B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lessons learned database for design engineers in Lotus Notes</td>
<td>Lessons learned documentation stored in local file areas or in the ERP System</td>
</tr>
<tr>
<td>Best Practices database for design engineers on the intranet</td>
<td>Issue reports for tracking problems in ERP System</td>
</tr>
<tr>
<td>Global database for standardized manufacturing processes for manufacturing engineers</td>
<td>Design Practices database for design engineers on the intranet</td>
</tr>
<tr>
<td>Lessons learned database for manufacturing operations on the intranet</td>
<td>Database with measurements from all manufactured components used by manufacturing operations</td>
</tr>
<tr>
<td>Experience reports from concluded projects on local file areas or in physical folders</td>
<td></td>
</tr>
<tr>
<td>Database with in-line measurements used primary by manufacturing operations</td>
<td></td>
</tr>
<tr>
<td>Database for tracking problems in manufacturing</td>
<td></td>
</tr>
</tbody>
</table>
Company A has a product development process that specifies that lessons learned should be reported at every gate and also consulted at certain points. However, this has not come fully into practice and there are not that many lessons learned available since this has recently been introduced. Experiences should be documented at the end of each project; however these reports are often filed on electronic project areas with restricted access. Design practices are created and managed by workgroups in organizational development work. There does not seem to be a process that triggers an update or creation of a design practice and employees express a lack of them. Similar to the automotive company, there is a vast collection of measuring data from manufacturing. This data is only used by manufacturing, even though the information would help design engineers to know more about the current manufacturing capabilities.

When design engineers were asked to rate how valuable best practice and lessons learned documentation is in their work, the response were quite scattered. Notably, 21% resp. 23% of the respondents was unaware of any lessons learned at all. Comments from the respondents were that it is difficult to find relevant information in the documentation.

4. Discussion
Two observations were evident from the study. One is the visible differences between the companies in the responses, and the other is the differences when comparing the response between different disciplines. The first observation is for sure impacted by the history and role of each company but also, at least partly, reflecting the difficulties in achieving an effective system for re-using manufacturing experiences in design. It is noticed that Company B has a more developed system to manage experience and are more aware about their processes for capturing manufacturing experience. Still, Manufacturing Operations convey an even higher frustration over recurrent manufacturing problems. One possible explanation could be that an increased awareness of the complexity of problems increases the receptivity and also the motivation to solve the problem. Explanations may also be found in the fact that Company B produces a car – a consumer product that can easily be related to and also a complete system. Company A produces engine components (each of the same cost and value as a car) but the complexity is of a different character when it comes to manufacturing.

The second observation, that experiences are captured and used by different disciplines, in different context is interesting. Typically, a vast amount of documentation is stored in databases and project areas and re-use is limited (in both companies). One suggestion is to update instructions and best practices according to selected lessons learned that are considered the most important for future products. Lessons learned activities at project start ups is a good opportunity to learn from the previous project, but can not replace the benefits of standardized best practices in the long term. Converting lessons learned into best practices may also help design engineers in the sense that there is no need to distinguish when lessons learned from similar cases apply to the current situation. More principally, the challenge is how to contextualize experiences from the "capture" context to the "use" and "re-use" context of design.

5. Conclusion
Three plausible mechanisms for re-using experiences from manufacturing in design were studied empirically at two manufacturing companies. As an indicative measure of effectiveness of re-using experience the perceived re-occurrence of manufacturing problems between product generations was gathered and revealed the percentage of reoccurrence was significant at both companies but higher at the Company B which have a longer tradition of own product development. Secondly, the involvement within early phases of design was studied, and the most significant result was that Company A had a fewer number of manufacturing engineers participating in design than within company B. Finally, the amount of formal processes and dedicated systems for feedback was higher in Company B that in Company A. Yet – the awareness and perceived effectiveness of systems and processes were low at both companies. In addition, the risk of "information overflow" is apparent once the formal
systems for capturing experiences are used. As the amount of information grows, it is known from interviews in the automotive company that design engineers prioritize other engineering tasks and are reluctant to follow the procedure to go through the sources of manufacturing experience. The conclusion is that despite long term experience and existence of both formal processes and IT systems, the perceived effectiveness of how to re-use manufacturing experience in design is still immature.

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REFERENCES

**Paper A**

*Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective*


**Paper B**

*Manufacturing system to support design concept and reuse of manufacturing experience*


**Paper C**

*Manufacturing experience in a design context enabled by a service oriented PLM architecture*

Manufacturing system to support design concept and reuse of manufacturing experience

Andersson Petter 1,2, Isaksson Ola 1,2
1 Department for Product Development and Methods Improvement, Volvo Aero, Trollhättan, Sweden
2 Functional Product Development, Applied Physics and Mechanical Engineering, Luleå University of Technology, Sweden

Abstract
Life cycle responsibility for manufacturing companies increases the service content coupled to the product. One consequence is that transferring knowledge gained from all life cycle phases has an even more decisive impact on the definition of the product concept, here referred to as the functional product. The paper focuses on transferring experiences from the manufacturing phase and how to account for these in the design phase. Based on an empirical study at two companies, an automotive and one aeronautical company, current practices were identified. Manufacturing experiences are captured and managed in a manufacturing context whereas the use of experience in the design phase is discussed. Finally a generic approach to support the use life cycle experiences in earlier phases of product development is suggested, where the design and manufacturing case serves as an example.

Keywords: Product Development; Manufacturing Experience; Manufacturing; knowledge sharing; Engineering design

1 INTRODUCTION
Life Cycle Responsibility increases amongst manufacturers today. The industry is challenged to understand different life cycle phase’s impact on the product, e.g. manufacturing, operations/usage, disposal etc. These factors are “product” focused whereas life cycle dependency implies accompanying services, such as maintenance and repair, customer training etc. The term used for products, having a service content, is called “Functional Product” (1), whereas Product Service Systems is used in a similar manner. The service integration in manufacturing challenges the competences, roles and responsibilities of manufacturing companies (2).

Consequently the emphasis on information and knowledge increases for manufacturing companies as the use and re use of experiences from various life cycle phases increase (3). Meanwhile, the impact that up stream processes such as the design phase has on the robustness and efficiency of manufacturing is well known.

A structured reuse of manufacturing experience involves incorporating learning from current or previous products in the design process in order to avoid recurrence of manufacturing issues on new products.

In the present study we have investigated how experiences gained in the manufacturing phase can be identified, adopted and eventually used in a designer’s context. This serves as a relevant example of where experiences are used from one life cycle to another.

The challenge to manage experiences and learning within manufacturing obviously cover a broad range of issues, where knowledge takes on many different forms. Even so the competitive power of succeeding in managing experiences in the organization is a strong motivator to continuously improve the experience management process (4).

In particular the feedback from manufacturing to tailor engineering design systems accounting for manufacturing experiences have also been discussed by Brissaud (5). They point out that the different context of the engineering designer versus the manufacturing context is missed out due to that experience management systems are often defined from a manufacturing context.

One approach is to take the viewpoint of the engineering designer, where the engineer’s context is enriched by integrating information from later life cycle phases. Boart et.al. (6) have shown that using the functional product development approach manufacturing process alternatives can be used as design parameters in early stages of product development. They argue that both the capability to quantitatively assess impact of varying Manufacturing Design Parameters, and the availability of these Design methods are needed to succeed as an early phase design method.

In the Design engineers’ toolbox, the CAE system plays an important role. The CAE environment has become a center point for the product modeling and much focus is set on the master model concept. Not only is the CAE used for geometric modeling (CAD), but for actually modeling the virtual product. As an example, template modules of parameterized CAD files are used to provide the design engineer with predefined blocks where rules are embedded in the parametric constraints (7).

At the same time as design methods focus on a master definition, the engineering environment gets increasingly heterogeneous with a dispersed set of data sources. Baily et al. (8) describes an “An Intelligent System for the Optimal Design of Highly Engineered Products”, where Knowledge Based Engineering is fused with product Control Structure, Conventional Master Model and Linked Model Environment to collectively render an Intelligent Master Model. This system provides multi-disciplinary design
optimization in a web based environment for global collaboration. In Europe, a collaborative platform for multi-partners and multi-engineering was developed in the European founded 6th framework project VIVACE (Value Improvement through a Virtual Aeronautical Collaborative Enterprise). [9]

2 CURRENT PRACTICES FOR CAPTURING AND USING EXPERIENCE FROM MANUFACTURING

A study was conducted at two companies, one in aerospace and one in the automotive industry with the aim to understand the current practices for capture and reuse of experience, i.e. engineering knowledge, in manufacturing. The study was defined to cover four product development phases; concept, detailed design, manufacturing preparation and serial production in three different organizational disciplines; design engineering, manufacturing engineering and manufacturing operations, according to Figure 1.

Questionnaires were used including, one department from each discipline, giving approximately 180 forms to analyze. The questionnaires where performed prior to the interview and both the questions and the preliminary result from the survey was used as a basis for discussions in the interviews. A report [10] from this study points out that it is common with recurring problems, although the frequency of them is perceived quite differently among the respondents. The perceived involvement where significantly different between the design engineers and manufacturing engineers in early phases, where the manufacturing engineers indicated a much lower level of collaboration.

It was also noted that manufacturing experience from earlier projects is usually made available through the composition of new design teams where competence from the manufacturing disciplines is included. Even so, 90% of the respondents believed there will be less recurrent manufacturing issues if collaboration between manufacturing and design increased. The usage of experience databases where also investigated and it was found that as the amount of information grows, the design engineers prioritize other engineering tasks and are reluctant to follow the procedure to go trough the sources of manufacturing experience.

3 CHALLENGES FOR REUSE OF MANUFACTURING KNOWLEDGE IN ENGINEERING DESIGN

From a design engineering point of view the experiences as perceived, captured and partially logged/documented is typically "atomized", i.e. found in the explicit manufacturing context. These "Elements of manufacturing experience" (EME) are different in character and format, e.g. experience related to manufacturing is; Problem reports, statistical information, list of operations, product structure as well as reports of experience from projects that are stored in Lessons learned databases.

3.1 Heterogeneous environment

The information is stored in different vaults and is usually accessed through special tools. Consequently EME exist in a heterogeneous environment, See Figure 2.

Manufacturing Execution System

The Manufacturing Execution System is a set of integrated functions which provides an infrastructure and a production management system. One of these functions is to collect statistical outcome from the production e.g. Cp, Cpk, etc. This data is used to follow up manufacturing requirements to ensure a robust manufacturing process.

Enterprise Resource Planning

In the companies Enterprise Resource Planning (ERP) system, various data and processes of an organization is integrated into a unified system. Examples of modules in an ERP system are, Financials, Projects, Human Resources, Customer Relationship Management, Supply Chain Management and Manufacturing, where the latter provides information about Manufacturing Process, Manufacturing Flow, Quality reports, etc. Consequently, the ERP system can provide a large amount of manufacturing experience.

Product Data Management

The PDM environment is usually tightly integrated with the CAD system for the management of product data related to the geometry definition. This system is also providing the link between product definition and manufacturing engineering task, such as lists of operations sequences and NC programs.

3.2 Design context verses manufacturing context

Different character of more or less isolated data elements that is stored from a manufacturing context/view. This problem...
has been approached in Data Mining [11] where intelligent tools for extracting useful information and knowledge has been developed but the context of usage in a designer’s context remain. As mentioned in chapter 2, experience
Databases tend to be large and often difficult to grasp.
Although a product development project is working with the same goal, to produce the best product possible, it is a natural tendency in larger organizations to experience a distance between people in different organizations. This gap is not only manifested in human to human communication, but is also apparent in the surrounding system environment. See Figure 3.
As an example, the design engineers work in a CAE environment that provides full access to component structure and the master definition. Although the manufacturing engineers work in the same system, they have a different view and limited access of the product structure, as there role is to grab an existing component definition and create a list of operations to be executed on the shop floor.
From the other side, manufacturing operations has a set of tools, generally referred to as the Manufacturing Execution System (MES), providing an interface between the manufacturing engineers and the operator of a machine.

![Figure 3. Reuse of manufacturing experience.](image)

The study revealed that although systems for capturing manufacturing experience existed within the manufacturing organization, the knowledge of its existence or how to access the information was not common knowledge among design engineers. In Figure 3, the feedback loops from manufacturing operations are also visualized, both the explicit type with a system integration shown with dotted lines as well as the implicit type with a human to human transfer.

1. The shortest feedback loop goes from manufacturing operations back to the production system (MES) and can be a fully automated process where NC programs are adjusted based on sensor signals integrated in the machine. Experiences here are quite close to data patterns, and local in character. The context is far from the designer’s context.
2. The feedback of information from manufacturing operations back to manufacturing engineering effects decisions regarding production flow, tools and machines. The manufacturing engineer has a central role in managing experiences in this phase.
3. Knowledge about manufacturing impact of design decisions made by the design engineer has an ever greater impact on the PD life-cycle and therefore a possible greater impact on product cost.

4. Manufacturing feedback to the CAD environment is still limited and usually a process of updating embedded rules. If successful, the embedded rules directly in the design tools can be quite powerful whereas the process of doing so may be sensitive and difficult to keep updated.

### 4 TOWARDS A DESIGN SYSTEM TAILORED TO MAKE USE OF EXPERIENCE

It is a necessity to understand the view of the receiver in the feedback loop and the engineering environment that surrounds him. How does the “element of experience” on the atomic level relate to his view? In more detailed example, how do we make the design engineer understand the meaning of statistical data presented from an individual milling operation? The result could be highly dependent on previous operations and the status of that machine at that particular time. What type of geometry topology is data related to? What project?

To answer these questions the design engineer needs to have a clear view of how the EME relates in the context of engineering design. Figure 4 describes the feedback loop in a design to manufacturing context where an element of manufacturing experience, in this case a statistic report of characteristics such as Cp and Cpk are presented in:

- a) The context of component structure
- b) The associated manufacturing process
- c) The process activity, the milling operation.

In the same context, a problem report is presented for a drilling operation, prior to the milling.

![Figure 4. EME in a component and process context.](image)
The consequence of this approach has many dimensions as it relate to several different business systems. It highlights important issues such as setting requirements on transparent interface protocols, neutral formats, etc.

Requirements on a design system that integrates experience use

1. Need to interactively search, find, retrieve and integrate experience related information from several different sources
2. Need to keep the experiences up to date close to real time
3. Need to build on the designer’s context and expand functionality rather than building a completely new tool.

5 CONCLUSION AND DISCUSSION

It is noted that the Functional Product approach clarifies the principal need to transfer knowledge and experiences between different domains, illustrated in Figure 5.

If the traditional focus has been to define a product based, mainly on a functional requirements perspective - a Functional Product perspective highlights the need to account for knowledge from all life cycle phases. The contextual challenge for design teams increases further, and making experiences available for a designer is a challenge. The situation in this paper has focused on the manufacturing process, but the challenge is universal and the argument is that the contextual diversity increases as life cycle dimensions are introduced in the product concept.

It is also noted that there is a demand for more manufacturing capability information in the concept phase, both in order to predict cost and to avoid recurrence of manufacturing issues. Finally, to achieve an effective reuse of manufacturing experience for the designer it is important to provide the feedback in the design environment, giving the design engineer access to information in a context he can understand.

6 REFERENCES

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Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective

Paper B
Manufacturing system to support design concept and reuse of manufacturing experience

Paper C
Manufacturing experience in a design context enabled by a service oriented PLM architecture
ABSTRACT

An increased competition on the product development market pushes the industry to continually improve product quality and reduce product cost. There is also a trend towards considering a product's life cycle aspects including environmental sustainability. The manufacturing process is a major cost driver in the product life cycle; hence, there are many initiatives to improve manufacturability and reduce production cost. Learning from earlier projects is essential to avoid recurrence of problems and is generally realized through use of concurrent engineering and design for manufacturing (DFM). Other research provides general DFM principles which state detailed guidelines for how different geometries combined with different manufacturing processes affect component quality and cost. The real competitive edge lies however in the development and application of company specific DFM principles which are based on manufacturing experiences. To do so requires an overview of and access to the collected manufacturing experiences. The aim of this paper is to point out key enablers for efficient reuse of manufacturing experience, which is considered to contribute to lower product cost and higher product quality.

A study performed at an automotive and an aerospace engine manufacturer pointed out the apparent need and lack of reuse of manufacturing experiences in product development. Applications supporting reuse of manufacturing experience through embedded DFM knowledge in designer’s CAD system were found in the literature. The issue of integrating these applications with the enterprise environment, in order to capitalize on existing sources of manufacturing experiences, is addressed with a proposed solution applying a service oriented PLM architecture. In addition, a graphical user interface visualizing the manufacturing experience in a combined product and process context was developed. The validation of these proposed and developed solutions was done through interviews and workshops. The conclusions are that visualization of manufacturing experiences in a combined product and process context provides improved understanding of how the experiences relate to each process history and that a key enabler for integration of information in heterogeneous environments is the use of standard service oriented architectures and neutral formats.

1 INTRODUCTION

Globalization and intensified competition in the industrial world call for improvements in all Product Development Life Cycle phases and cross-disciplines. In the automotive and aerospace industry, the manufacturing process is in most parts a well integrated part of the Product Development (PD) process and it is still common with a collocated manufacturing shop floor. In this perspective, it is natural to include resources from the manufacturing functions in the earlier PD phases as a mean to share manufacturing experience from earlier projects. A pilot team in the concept phase is then assembled of expertise from other organizational functions such as design, CAE, market planning and sourcing. The shortcomings of such an approach becomes obvious in a large company with several stakeholders and where the knowledge base from manufacturing alone consists of up to 8 key persons. In addition to the difficulties to compose such a large group and the implications of keeping it efficient, the lack of resources is often a show stopper/obstruction. In order to provide access to e.g. knowledge and experience from manufacturing without having personal presence from the experts there is the possibility of developing expert and knowledge based computer applications which perform the most common expert tasks directly on the designer’s desktop. A problem however is that these applications’ input data is usually stored in a database specially developed to suit a specific need locally in manufacturing. Another problem is that there exists manufacturing experience that is explicitly available but is not suitable for a computer application e.g. comments regarding the design or regarding a workaround in
the manufacturing process in order to realize a complicated
design or other documents such as incident reports from
manufacturing. This experience is very valuable for those
working in earlier product phases in order to avoid mistakes
and complications from earlier projects.

Hence, the aim of this paper is to address two key
enablers for efficient reuse of manufacturing experience. These key enablers are:

- Access to manufacturing data
- Contextualization of manufacturing data from
  the receiver’s point of view

In section 2 a previous case study to investigate current
practices for reuse of manufacturing experience are described.
In section 3 some of the most relevant work related to this
contribution is summarized. In section 4 the concept of a
service oriented PLM architecture is explained. Section 5
describes how the accessed experience is made available to the
designer by putting it in a combined product and process
context, thus making it more understandable. Section 6
describes why a service oriented PLM architecture enables the
proposed contextualization better than currently applied
solutions. In Section 7 the demonstrator that will implement
the results from section 4 and 5 is described and explained in
detail. Finally in section 8 a discussion around the subject and
future work are proposed and the paper is concluded in section
9.

2 STATE OF THE PRACTICE

Prior to this work, an empirical study was carried out at
one automotive and one aerospace industrial company [1], [2].
The aim of the study was to understand the current practices
for capture and reuse of experience, i.e. engineering
knowledge, in manufacturing. The study revealed a
heterogeneous environment with several different sources of
manufacturing data. Examples of sources for experience were;

- Lessons learned database for design engineers
  in Lotus Notes
- Best Practices database for design engineers on
  the intranet
- Global database for standardized manufacturing
  processes for manufacturing engineers
- Lessons learned database for manufacturing
  operations on the intranet
- Experience reports from concluded projects on
  local file areas or in physical folders
- Database with in-line measurements used
  primarily by manufacturing operations
- Database for tracking problems in
  manufacturing.

The study showed that the automotive company has a
more developed system to manage experience and are more
aware about their processes for capturing manufacturing
experience. Despite this, Manufacturing Operations convey a
higher frustration over recurrent manufacturing problems. One
possible explanation could be that an increased awareness of
the complexity of problems increases the receptivity and also
the motivation to solve the problem.

The study also revealed that although systems for
capturing manufacturing experience existed within the
manufacturing organization, the knowledge of its existence or
how to access the information was not common knowledge
among design engineers.

A set of requirements on a design system that integrates
experience use was identified:

1. Need to interactively search, find, retrieve and
   integrate experience related information from
   several different sources
2. Need to keep the experiences up to date. As
   close to real time update as possible
3. Need to integrate in the designer’s context and
   expand functionality of existing tools rather than
   building a completely new tool

3 RELATED WORK

The paper applies results from several different areas
which relate to the general subject. Related work from each of
these areas is briefly summarized below.

3.1 Knowledge based engineering and DFM

The integration of manufacturing experience and
knowledge in product development generally referred to as
design for manufacturing (DFM), is a well established
approach for increasing the manufacturability and quality and
at the same time decreasing the costs of the designed products.
General DFM principles which state detailed guidelines for
how different geometries combined with different
manufacturing processes affect the component quality and cost
can be found in e.g. [3].

Examples of implementation of DFM in internally
developed Knowledge Based Engineering (KBE) techniques
has been used as an approach to provide manufacturing
knowledge in early development phases [4], [5], [6], [7]. The
focus of these examples is to demonstrate different ways of
incorporating manufacturing knowledge and experience
through design automation and usually require manual
handling of inputs and outputs.
There is however a need to provide these kinds of applications with inputs derived from e.g. databases containing results from manufacturing processes, which today are used for quality management purposes, in order to feed product design with accurate and up to date information from manufacturing.

An area approaching this is data mining where intelligent tools for extracting useful information and knowledge have been developed but the context of usage in a designer’s context remain.

When simulating the manufacturing processes in order to obtain desired product properties in the final product, it is essential to include the entire manufacturing process sequence in these simulations [8]. In this paper we argue that it is equally important to include the full manufacturing process sequence when feeding back manufacturing experience in the early phases of product development.

Molina et. al. [9] demonstrates a system that utilizes web-based applications to, at the concept level, allowing a designer to describe a part so that an expert system can decide which manufacturing processes can produce the desired part, in the desired time, with the desired quality.

Other work on reuse of manufacturing experience is done by Alizon et. al. [10], presenting a method that considers similarity, efficiency and configuration when identifying similar existing designs to a desired one defined by the engineer.

### 3.2 Service oriented PLM architecture

Service oriented architecture as a software engineering principle has been around for many years but it is only recently with the increased maturity of web service technology that this kind of loose integration has been applicable. With rising insights regarding IT support of engineering processes especially related to issues of product documentation and the supplier lock-in phenomenon the principle of service orientation has been abstracted from basic software principles to integration of systems. The purpose of this is the fact that the product is documented in different systems containing bits of information about the product and in order to obtain a complete view of the product these information bits need to be gathered which means the underlying systems need to be integrated [11], [12]. From this perspective the systems are viewed as providers of information services which deliver these information bits. These ideas led to the development of a standard for how design of these abstracted services is to be implemented called PLM Services 2.0 and provided by OMG [13].

An implementation of the standard has been performed and the results seem very promising [14]. There are several works done which describe the possibilities of improving different parts of product lifecycle management through the application of a service oriented architecture [15], [16], [17], [18], [19], [20].

There are also other proposals for the realization of a service oriented PLM architecture, one of which is proposed by another standardization body called OASIS [21]. An implementation of this standard is found in the European VIVACE project [22] in a demonstrator for supporting the idea of an extended enterprise using a hub solution [23] that applies web services according to the OASIS standard for integration with other systems.

### 3.3 Contextualization

The importance of a contextual approach is widely recognized within Knowledge Management and the emerging field of IT/web collaboration tools.

The definition and use of context as a concept has been analysed by Dey and Abowd [25] use context to provide task-relevant information and/or services to a user. The context is here primarily of four types; location, identity, time and activity.

In the European project VIVACE [22], a context based search platform was developed [26]. As part of the study, two approaches regarding a context model were studied, a top down approach and a bottom up approach. In the top down approach is the engineering context defined as any information that can be used to characterize the situation of an engineer. The bottom up approach deals with the problem of categorizing data/information and the recognition of new circumstances where the knowledge source could be usefully applied. A key issue concluded here is the importance of providing the right knowledge to the right user at the right time in the design process.

### 4 SERVICE ORIENTED PLM ARCHITECTURE

A service oriented PLM architecture implies that every source of data and information is viewed as an information service provider [11]. This is illustrated in Figure 2 where every information source publishes its available information services in a service registry. The registry is accessed by the user applications to search for the information they need. The service registry then appoints the user applications to the correct address of the information as published by the information sources. The information access and delivery is
then performed according to a contract that states how the information is accessed and delivered. The contract also states in which format information is delivered. In this case study a standard contract for the services, called PLM Services 2.0, is considered.

The primary purpose of a service oriented PLM architecture is to make sure that all the data gathered and stored throughout the product lifecycle is made available and can easily be accessed for different purposes. These purposes can vary; examples could be development of applications which apply aftermarket knowledge to analyze a packaging solution of a vehicle, calculate exact production cost for a given design, provide better support for strategic product portfolio decisions, provide analyses of material suppliers in real time for purchasing and so on. Even though all these examples could be realized by developing special databases for each purpose most of the time the data needed already exists in some form and in some database. If there is business value in developing an application such as the ones mentioned in the examples this value should not be decreased or wasted due to the fact that data needed for the application is difficult to access. This is depicted in Figure 2 where the underlying information and database layer offers bits of information, provided as information services, thus making information accessible for the applications which support users.

4.1 PLM Services 2.0

An important enabler for service oriented PLM architecture to work is the “service contract” according to which information is communicated. The standard contract PLM Services 2.0 is provided by the standardization body Object Management Group (OMG) [13] and has been developed together with representatives from the German automotive industry. PLM Services 2.0 standard provides the developer of the service oriented architecture with the contract according to which information is to be communicated.

What makes this standard special is that its starting point are the common workflows encountered in the PLM area and its aim is to support engineers working with product development. This is however not to be confused with processes and workflows which are embedded in commercial PLM software suites due to the fact that the workflows in the standard are at a more generic level (due to the fact that they are not restricted to the use of any particular software for PDM nor for CAx). This means that there is flexibility to have company specific processes, applications and information.

The standard defines a STEP AP214 compliant data model and all the necessary functionality to realize several use cases. OMG supplies the XML schemes and WSDL (Web Service Description Language) files that define PLM Services. The WSDL files supplied by OMG specify three web services, Connection Factory, General Connection and Message Connection. The Connection Factory service contains method skeletons that handle authentication and the creation of sessions and acts as a gateway to the other two services. The General Connection service includes method skeletons that handle communication based on the request/response approach. To pass PLM data, it uses instances of the class PLMCoreContainer. To request data from the system, it uses instances of the class PLMQuery. The Message Connection service includes method skeletons that handle communication based on the message exchange approach. It provides methods to query messages from a service, to write messages to a service and to delete messages from a service. The service layer setup is depicted in Figure 3.

5 CONTEXTUALIZATION OF INFORMATION

Providing access to data and information is an important and necessary first step but not always enough to support the processes in an effective manner. This only addresses the service oriented integration part of SOA in which the information sources are integrated with each other but there are no considerations of how the processes are integrated with the information. When the information sources are integrated possibilities and needs arise to change the processes in order to optimize the complete process and IT environment. Since a service oriented integration enables access to more information which has its origin in company departments who have another view of the product it will have another format due to the differing context. In the particular case of reuse of manufacturing experiences in design the information is created and stored in the context of manufacturing and thus it is formatted to support manufacturing needs. Therefore the information needs to be put in a context so that the receiver of the information is able to understand it in order to support the process the receiver works in.
Two issues regarding the contextualization of information have been identified:

1. Information format
2. Information presentation

The issue of information format refers to the fact that the information is formatted in order to support a process in its original context. This means that the information needs to be reformatted in order to support another process in a different context. The issue of information presentation is simply the way in which the information, once accessed and reformatted, is presented to the user in order to support the user’s process. The two issues related to contextualization can be addressed in several ways, two of which are:

1. Presenting the accessed information in a specific graphical user interface (GUI) which is suited to the user’s context. The specific GUI implies that the information needs to be formatted in a logical manner to the user but the user needs to execute the process for which the information is needed.
2. Implementing a specific application which will use the accessed information as input, perform the process which the information supports and present the result to the user. This solution implies that the application needs to understand the format in which the information is accessed.

Which of these solutions is better to choose depends on the context and the process which is to be supported.

### 5.1 Product and Process context

In this case study the issue of contextualization has been addressed by applying a combined product and process context. To only use the product structure, which ever structure it may be, to structure experience is suitable for e.g. design guidelines but lots of experiences relate to specific activities during design, manufacturing, sales, service etc and therefore the process aspect is needed as well. When considering experience related to a component it will be part of a system that performs a function, taken from the designer’s view of the product, but the component will be part of a subassembly, taken from the manufacturing engineer’s view of the product. This issue of different product views is addressed by a specific chromosome model [27] which can be used to bridge the two contexts by relating two different product structures. The issue of process related experiences remains however unsolved.

In the particular case of reuse of manufacturing experience the experience is related both to the manufactured components which can be structured in assemblies viewed from the manufacturing point of view. But it also relates to the different steps of the manufacturing process. Therefore there is a possibility to select a component and reach all the experience related to this component from all the manufacturing steps. By applying the process context onto the product context it is possible to also select an activity in the manufacturing process and only view the subset of experience related to the selected component and selected manufacturing step.

Finally there is also a possibility to only consider a manufacturing activity, e.g. welding, and not consider any components in which case the experience will relate to welding in general.

Completing this with the chromosome model which relates components with functions we come even closer to the designer’s context. This means there is a possibility to e.g. view all experience of welding related to a specific function which enables the bridging of manufacturing experience from the manufacturing to the designer’s context as depicted in Figure 5.

### 6 SERVICE ORIENTED PLM ARCHITECTURE AS ENABLER FOR CONTEXTUALIZATION

In this section the issue of using a service oriented PLM architecture for enabling contextualization is compared to the state of the practice enablers. The example from Figure 4 will be used to illustrate and discuss the differences of the described solutions. In the example a fictive process of cost estimation is supported. From a process point of view it will be best supported by implementing a cost estimation application which needs the listed pieces of information as input in order to produce an estimate as output. Thus the contextualization of information from four different contexts to the design context is performed by a specific application. The application will present the final information, the cost estimate, in a way and in a format which is best suited from the designer’s point of view.

In Figure 6 a common state of the practice is described. A cost estimation expert either designs an application himself or helps an application designer to design a cost estimation application. The application is designed by hard coding the different pieces of information into the application. This usually leads to issues regarding the fact that it is costly and time consuming to develop different applications to support the development of different product variants why either the most common variants are supported or the hard coded parameters are balanced and their values are approximate. The hard coded parameters need to be updated after a while and the application needs to be maintained.

![Figure 5 – Bridging experience from manufacturing to design context](image)

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These circumstances lead to increased costs for the development and maintenance of the application which means that the overall financial gain in the process is decreased. The application costs might even be so high that the financial gain is lost and the application is not implemented even if it may increase product quality which is hard to measure exact financial gains from.

Figure 7 depicts another solution which is about creating interfaces in order to integrate information sources and applications. This approach addresses the issue of not having to balance different parameters due to product variants in the application which means the process will be supported in a better manner. The approach will however lead to a lot of hard coded integrations with many to many integrations which themselves increase maintenance costs when IT vendors change their interfaces in new releases. The flexibility of changing processes is decreased and the changes with minor financial gains will not be implemented due to interface development costs.

In Figure 8 a service oriented PLM architecture is used to enable the contextualization. The cost estimation application accesses the information service layer and requests the information it needs for its process of cost estimation. This approach addresses the issue of not having to balance the parameters as is the case in the hard coded application in Figure 6. At the same time the coupling to the underlying information sources is not either hard coded through direct interfaces as in Figure 7. The loosely coupled SOA approach does however imply that the information needs to be in a neutral format according to the service contract. This is required in order to provide the needed flexibility since a neutral format will mean that every information source and every information consumer will only need to have one interface which is needed to deliver/access the information. The most optimal approach is to use an information standard which is supported out of the box by the information sources.

7 DEMONSTRATOR

The aim of the demonstrator is reuse of manufacturing experience in early design phases. The general purpose for why this focus is chosen has been addressed in sections 3 and 5. The studied case contains all of the issues that have been described so far. More explicitly these are:

- The manufacturing experience considered is stored in four different systems.
- The format of the information carrying the manufacturing experience is adapted to the manufacturing context, not design.
- Once accessed and reformatted the information needs to be presented in a way which is natural and logical from the designer’s point of view.

Schematically the demonstrator architecture is depicted in Figure 9. In Section 5.1 it was described how a product and process context was used to create a bridge for manufacturing experience from the manufacturing context to the designer’s context. Technically this will need to be done by implementing a neutral information model in the service layer. This provides the desired flexibility that is one of the main reasons for choosing a SOA. This means that all the information sources and information consumers need to be able to communicate to the neutral format.

The manufacturing experience consists of measurement data stored in a legacy system, production preparation documentation stored in Siemens TeamCenter, operator comments stored in a legacy system and incident reports stored in SAP R/3. To cope with these issues there is a special process that states the order and type of the different queries.
needed to access and gather information on one hand and define the context in which the accessed information will be logical to the designer on the other. The different steps were needed due to the fact that in some databases data is structured according to the structure of manufacturing requirements, in some according to the manufacturing process and in some according to different projects. But what the designer wants to see is the data structured according to the function structure and component structure.

The access to and integration of the four different information sources will be enabled by a service oriented architecture. A similar approach has been reported by Chen et al. [18] where a typical collaboration manufacturing model for virtual manufacturing enterprise alliance is presented. For the SOA implementation the standard PLM Services 2.0 is considered in order to evaluate the standard and also enable the desired demonstrator characteristics. This approach has been chosen in order to enable the flexibility to expand the scope of the demonstrator and to also enable for other existing or new applications/portals to access the information that is made available through this integration. The flexibility also enables the integration of more information sources.

The presentation of the accessed and reformatted information is done by a client application with a specific graphical user interface (GUI). The client application contains the function structure and component structure to which information from the information sources is linked and presented.

A screenshot of the GUI is shown in Figure 10. In the main area there is the ability to switch between the component structure and function structure. There is also an ability to apply a project filter in order to only show manufacturing experience related to a specific development project.

Figure 10 – Graphical User Interface of the demonstrator

In the process area the manufacturing process for the selected component or function is presented. The process is stored in Siemens TeamCenter. In the area where quality notifications and manufacturing data is presented operator comments, stored in SAP/R3, and data from manufacturing measurements, stored in a legacy database, will be presented for the selected component or function. The same is done in the area showing manufacturing requirements which are stored in SAP/R3. The amount of results in these two fields can be narrowed down further by choosing a specific manufacturing activity.

The workflow for the demonstrator is that the designer chooses the function/component and/or project whose manufacturing experience he/she is interested in. The process field is automatically updated showing the manufacturing process for that particular component/function. Quality notifications, manufacturing data and manufacturing requirements for that particular component/function are automatically updated. If the designer is interested in manufacturing experience related to a specific step in the process, e.g. welding, the requirements, manufacturing data and quality notifications are updated so that they now only show information relevant for the chosen component/function, project and the welding step of the process.

The layout of the GUI along with the fact that information will be dynamically accessed and presented as the user selects components or functions creates the context in which the manufacturing data becomes more logical from a designer’s point of view.

8 DISCUSSION AND FUTURE WORK

The focus of this paper has been to describe a solution for the re-use of manufacturing experience in early lifecycle phases in order to make the product easier and faster to produce. The general and more abstract idea is that information gathered in a later lifecycle phase is fed back to earlier phases in order to be able to optimize the product over a larger portion of the lifecycle. The described concept can be extended to include all lifecycle phases so that the optimization of the product can extend over the whole lifecycle thus enabling the realization of product lifecycle management to a greater extent. The experience can be in the form of documents such as design guidelines but it can also be
documented in the form of video clips or online demo presentations such as those exemplified at Honeywell [28].

Using the process, together with the product, as a means for structuring different kinds of experiences has been found to be feasible and will be further evaluated. By applying the process perspective experience from e.g. calculations performed during the development or service actions performed during the aftermarket of a component or even an individual of a component can be made accessible in an easy way. Developing the proposed GUI to entail also other processes in the product lifecycle and make experience from those lifecycle phases available will not be a large task due to the generality of the proposed GUI structure. The access to the information sources containing the experience will be secured by connecting those sources to the information service layer.

The future work entails the development of the information service layer described in Sections 4 and 5. The developed demonstrator, once the service layer is implemented, will be expanded by another way of contextualizing the manufacturing experience. The information will be made available even closer to the designer and the designer’s context by connecting a CAD integrated KBE application which will use the manufacturing experience in order to optimize component from a design for manufacturing perspective and be able to take into account the latest information from the manufacturing system.

9 CONCLUSIONS

This paper concludes that contextualization of and the ability to access manufacturing data in real time are two key enablers for providing design engineers with manufacturing experience from earlier and ongoing projects. The approach to visualize data from dispersed sources in manufacturing using web technology and with a design engineer's perspective provides a powerful engineering tool in the early phases of product development. The service oriented PLM architecture enables access of manufacturing experience in a dispersed system environment and provides the possibility to integrate knowledge based engineering applications which focus on DFM in order to provide them with real time input data from manufacturing.

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