THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Product Lifecycle Management
– Architectural and Organisational Perspectives

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ABSTRACT

This thesis investigates Product Lifecycle Management (PLM) with focus on architectural and organisational perspectives. The increased complexity in industry regarding processes, IT systems and organisation makes it difficult to manage product information from several and traditionally different engineering fields. It is evident that it is no longer possible to design a product without sharing information across the company. This is where PLM will play a large and important role in streamlining the information flow in the industry of tomorrow.

The two themes for the research, architectural and organisational perspectives, are connected with the identified research opportunity regarding introduction and improvement of PLM. From one perspective, the planning of the roll-out calls for structured and well-thought-through maps of the PLM landscape including processes and information, that is, the PLM architecture. On the other hand, the organisation needs to prepare for the large organisational change that constitutes PLM work. In combination, the PLM architecture and organisation studies complement each other and contribute to building purposeful PLM systems that will suit an ever-changing organisation.

The architectural perspective includes technical aspects of PLM and different integration concepts to integrate product development at product-developing firms. The focus of this part of the research has been mechatronic product development where mechanical, electrical and electronics, and software engineers need to collaborate efficiently. In this research several different PLM integration architectures have been evaluated, and specifically a service-oriented architecture (SOA) with relevance to PLM processes has been tested in demonstrators. The research concludes that flexible PLM architecture as offered by the SOA is beneficial for most companies since it allows flexible IT environments that can evolve over time, and can be enabled by a stepwise introduction.

The organisational perspective targets the great organisational impact that PLM and in particular PLM introductions have. Of specific interest is the PLM user, the engineer working in the product development process. This part of the research has led to development of methods and tools to manage the management and user perspectives, as well as statistical tools to identify problems with PLM and to cluster PLM users according to their specific needs. This part of the research concludes that it is important to involve the PLM user in the PLM deployment, and that goals and visions can be shared between both management and PLM users. Further, the statistical tools show promising results in order to identify target areas for improvement and to be used for better planning of a PLM introduction.

The research is essentially based on a qualitative approach employing interviews, combined with quantitative data collection, workshops, document studies, and demonstrator development.

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Special thanks go to my co-author of my latest papers regarding PLM and architecture, Lic. Eng. Amer Ćatić. We have had great discussions about research and business potential.

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Göteborg, March 2009

Dag Bergsjö

APPENDED PAPERS

The following papers serve as the foundation for this doctoral thesis. The papers are referred to as Papers A, B, C, D, E, F, G, and H and can be found in the Appendix.

Papers concerning PLM architecture and development:

Paper A (Bergsjö et al. 2006a)
Bergsjö, D., Malmqvist, J., and Ström, M., "Implementing Support for Management of Mechatronic Product Data in PLM Systems – Two Case Studies", Proceedings of IMECE2006, Paper no IMECE2006-14483, Chicago, USA, 2006.

Paper B (Bergsjö et al. 2006b)
Bergsjö, D., Malmqvist, J., and Ström, M., "Architectures for Mechatronic Product Data Integration in PLM Systems", pp. 1065-1076, Design 2006, Dubrovnik, Croatia, 2006.

Paper C (Bergsjö et al. 2007)
Bergsjö, D., Vielhaber, M., Malvius, D., Burr, H., and Malmqvist, J. (2007), "Product Lifecycle Management for Cross-X Engineering Design", paper no. 452, ICED'07 Paris, France.

Paper D (Bergsjö et. al 2009)
Bergsjö, D., Ćatić, A. & Malmqvist, J. (2009) Implementing a Service Oriented Architecture Focusing on Support for Engineering Change Management. Submitted to International Journal of Product Lifecycle Management

Papers concerning organisational perspectives on PLM:

Paper E (Malvius et al. 2007a)
Malvius, D., Bergsjö, D., and Molneryd, S. (2007) Balancing Operational and Strategic Impacts on Information Management, Las Vegas, USA, paper no. DETC2007-35438, Proceedings of the ASME DETC 2007.

Paper F (Malvius et al. 2007b)
Malvius, D., Bergsjö, D., and Molneryd, S. (2007) Shifting Lead as PLM Introduction Strategy. ICPLM'07. pp. 179-188, Bergamo, Italy.

Paper G (Bergsjö et al. 2008a)
Bergsjö, D., Malvius, D. & Christensson, C. (2008) Measuring IS/IT Performance – A Model to Identify Improvement Areas in Engineering Information Management Based on User Satisfaction. To be submitted to international journal.

Paper H (Bergsjö and Malvius 2008)
Bergsjö, D., and Malvius, D., (2008) Motivation Mapping Method as Means to Improve Engineering Information Management. Paper no. 1569089046, IAMOT 08. Dubai, UAE.

DISTRIBUTION OF WORK

Paper A
The study at the large company was performed in collaboration between all authors, while the study at the small company was performed by Mikael Ström. The demonstrator for the large company was developed by Dag Bergsjö, while the demonstrator for the small company was developed by Mikael Ström. The paper was written by Dag Bergsjö. Johan Malmqvist and Mikael Ström contributed ideas and as reviewers.

Paper B
The paper was written by Dag Bergsjö. Johan Malmqvist and Mikael Ström contributed ideas in the overall project and as reviewers.

Paper C
The study was initiated and the paper was written by Dag Bergsjö and Michael Vielhaber. Dag Bergsjö wrote the chapter on Engineering Change Management and Michael Vielhaber wrote the chapter regarding Configuration Management. All other chapters were written together. Diana Malvius participated in the workshop and contributed writing in the Introduction and Presentation chapter. The background study was carried out by Dag Bergsjö and Diana Malvius regarding the Swedish company, and by Holger Burr regarding the German firm. Johan Malmqvist contributed ideas and as reviewer.

Paper D
The empirical study regarding the turbo case was performed by Amer Catic. The detailed programming of the demonstrator was performed by Jonas Persson and Jonas Stiborg. Dag Bergsjö and Amer Catic wrote the paper together. Johan Malmqvist contributed ideas and as reviewer.

Papers E, F
The study was carried out and the papers were written by Dag Bergsjö and Diana Malvius together. Sara Molneryd helped in designing and conducting the interviews.

Papers G, H
The study was carried out and the paper was written by Dag Bergsjö and Diana Malvius together.

OTHER PUBLICATIONS

(Zimmerman et al. 2006)
Zimmerman, T., Bergsjö, D., and Malmqvist, J., (2006) "Coordinating the Engineering and Aftermarket Disciplines in Early Phases of Product Development", pp. 13-25, NordPLM'06, Göteborg, Sweden.

(Bergsjö and Malvius 2006)
Bergsjö, D. and Malvius, D., (2006) "Use of Information Management Systems from Designers' Perspective", pp. 179-190, NordDesign 2006, Reykjavik, Iceland.

(Ström et al. 2007)
Ström, M., Malmqvist, J., and Bergsjö, D., "Using PLM Systems to Manage Product Data of Mechatronic Products", IVF Industriforskning och utveckling AB, Mölndal, Sweden, 2007.

(Bergsjö and Malvius 2007)
Bergsjö, D. & Malvius, D. (2007), "A Model to Evaluate Efficiency, Quality, and Innovation through User Satisfaction with Information Management Systems", Proceedings of CSER'07, New York, USA, paper no. 13.

(Bergsjö et al. 2008a)
Bergsjö, D., Ćatić, A. & Malmqvist, J. (2008) Implementing a Service Oriented PLM Architecture Using PLM Services 2.0. *DESIGN'08,* pp. 271-280, Dubrovnik, Croatia.

(Ćatić et al. 2008)
Ćatić, A., Bergsjö, D., & Malmqvist, J. (2008) Integration of KBE and PLM in a service oriented architecture. *PLM'08,* Paper no: 166, Seoul, *Korea.*

(Malvius et al. 2008)
Malvius, D., Bergsjö, D. & Norell Bergendahl, M. (2008) Measurement of Information Management Systems Introductions. *Proceedings of ASME IDETC/CIE.* Paper no. DETC2008-50127, New York, USA.

(Bergsjö et al. 2008b)
Bergsjö, D., Ćatić, A. & Malmqvist, J. (2008) Towards Integrated Modelling of Product Lifecycle Management Information and Processes. *NordDesign 2008.* Tallinn, Estonia.

(Berglund et al. 2008)
Berglund, F., Bergsjö, D., Högman, U. & Khadke, K. (2008) Platform Strategies for a Supplier in the Aircraft Engine Industry. ASME DETC, paper no. DETC2008-49526, New York, USA.

ABBREVIATIONS AND ACRONYMS

AP214	ISO 10303 Application protocol for automotive mechanical engineering
AP233	ISO 10303 Application protocol for systems engineering
AP239	ISO 10303 Application protocol for product lifecycle support (PLCS)
BOM	Bill of Material
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CM	Configuration Management
cPDm	Collaborative Product Definition Management
CVS	Concurrent Versions (Versioning) System
ECM	Engineering Change Management
E-BOM	Engineering Bill of Material
EE	Electrical and Electronics
ERP	Enterprise Resource Planning
IS/IT	Information Systems and Information Technology
KBE	Knowledge Based Engineering
MBD	Model Based Development
PDM	Product Data Management
PLM	Product Lifecycle Management
RM	Requirements Management
SE	Systems Engineering
SysML	Systems Modelling Language
SCM	Software Configuration Management
SOA	Service Oriented Architecture

STEP	Standard for the Exchange of Product Model Data (ISO 10303)
UML	Unified Modelling Language

TABLE OF CONTENTS

1 INTRODUCTION

In this chapter the subject of the research is presented, with a presentation of the background and goals of the research work.

1.1 Background

Mechatronic products such as modern cars are rapidly moving into having more functions realised by electronics and software. A traditional mechanical function such as a braking system used to be realised by hydraulic pipes connecting the braking pedal with the drums or disks connected to the wheel. In a modern car, however, computers are connected to the brakes for calculating friction against the ground, the distance to the vehicle in front, and the speed of the car. Increasing the complexity even further, something as relatively simple as an automotive wheel (Figure 1) could be expanded to incorporate more and more functions, including suspension, brakes and an electric motor for propulsion within the same wheel module (Michelin 2008).

> *Mechatronics is defined as "a technology which combines mechanics with electronics and information technology to form both functional interaction and spatial integration in components, modules, products, and systems" (Buur 1990)*

Manufacturing firms are typically organised around specialised functionally oriented departments, and these departments have over time developed their own processes and IT systems in order to support their specific domain. In mechanical design, the focus has been on organising drawings, and since the late 1960s this has been done with computer support in databases that later developed into PDM systems. Over the years PDM systems were developed to support functions such as process management and configuration management for the mechanical discipline. The mechanical development has been the "core" process

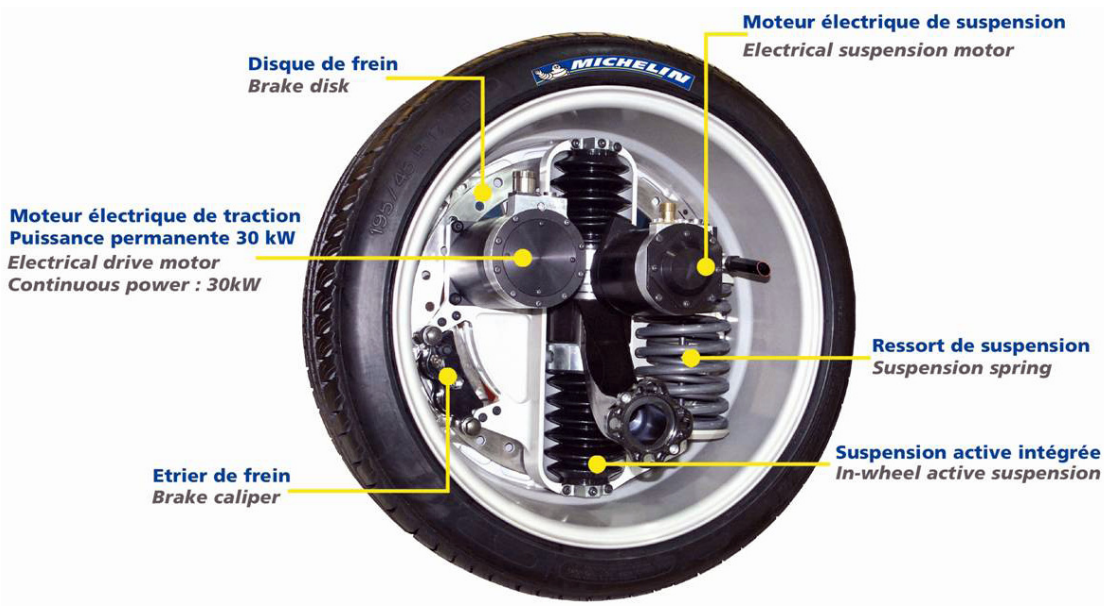


Figure 1. Wheel that incorporates mechanical, electrical and software

within traditional manufacturing firms such as in the automotive industry, and naturally the electrical components and wiring tended to be added after the mechanical design was finished.

> *"PDM is the discipline of controlling the evolution of a product and providing other procedures and tools with the accurate product information at the right time in the right format during the entire product lifecycle." (CIMdata 1998)*

Software and electronics have been closely related disciplines in manufacturing firms, since electrical functions started out as purely electrical and, during the past decade, have switched to being software-dependent. Software and electronics development has been characterised by iterations and concurrently existing solutions that are difficult to manage in PDM systems. In order to support software development, Software Configuration Management (SCM) systems evolved separately from PDM systems. As more functions are being realised by electrical and software functions, the traditional sequential versioning in mechanical engineering and their legacy of management of documents and solutions has led to difficulties in organisations. Multidisciplinary tasks such as engineering changes have become especially critical. For example, a design nowadays concerns not only holes in chassis, but complete mechatronic systems, which have made the engineering changes more costly and time-consuming.

> *Software "Configuration Management is the art of identifying, organising, and controlling the modifications to the software being built by a programming team." (Babich, W. A. as cited by Crnkovic et al. 2003)*

Interdisciplinary collaboration is central to the effective data management in the mechatronic product lifecycle, particularly where heterogeneous technologies, tools and working practices are involved. Ineffective management of information has had the result that engineers today must spend more time on information management than on engineering and innovation. Figure 2 shows how engineers spend their time (Coopers & Lybrand as cited by Saaksvuori

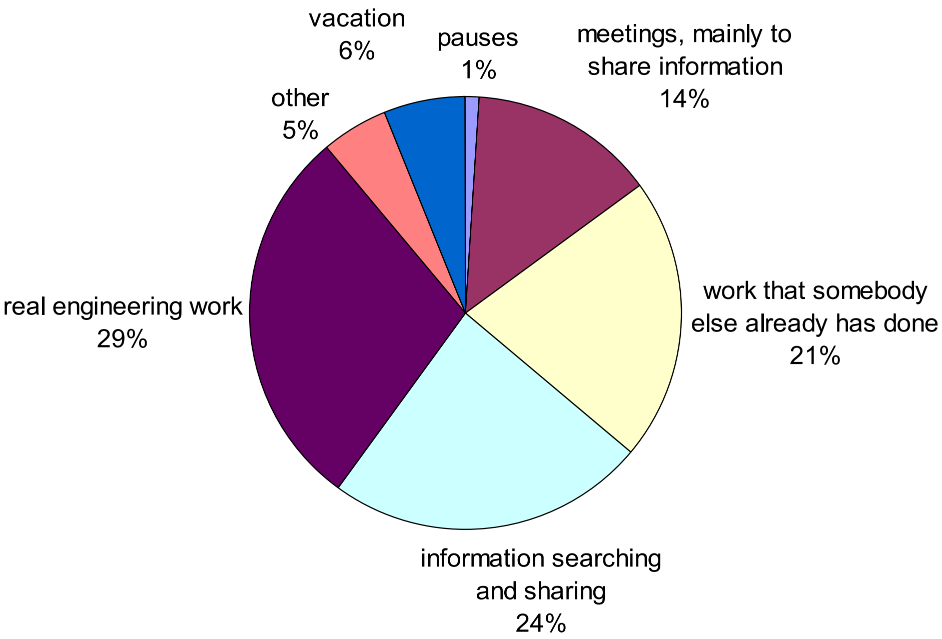


Figure 2. Time usage of engineers (Coopers & Lybrand as cited by Saaksvuori and Immonen, 2005)

and Immonen, 2005). The study in question showed that only one third of the designers' time was spent on tasks directly contributing to the product development. The conflict between a dominant mechanical department and the fact that more functions are realised by software and electronics has made it evident that different disciplines within the companies are no longer independent islands where each department has its own specific IT system – this does not work anymore. The diversity of the legacy IT tools and systems (illustrated to the left in Figure 3) makes collaboration and information exchange difficult, collaboration that is essential when working concurrently and e.g. performing engineering changes and managing variants of products.

In a legacy environment, several dependent IT systems have been created over time, in a way that is difficult to assess, and where a lot of information has been hard-coded. A homogeneous IT environment is difficult to achieve since IT systems and solutions are spread out in both time (development gates) and space (different departments). Integrating the development over several departments, totalling thousands of employees, calls for powerful IT tools and systems, where information can be managed for instant access. This concept is represented in Product Lifecycle Management (PLM). The way of performing this integration or architecture is going to be discussed in this thesis. Examples of PLM architectures are presented, such as the single-storage solution and the service-oriented architecture (SOA) depicted in Figure 3.

> *PLM is "a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems and information." (CIMdata 2002)*

PLM is not something that you introduce and then possess, like many other IT tools. In some ways PLM is something that all companies have to some degree and have always had. It is more about expanding and evolving the companies' needs for information management over time. A PLM introduction, as it is referred to in industry, is thus more of a change of the information management and a step (small or large) towards better information management. Hence, PLM introductions are as much about organisational change and knowledge management as about a "big bang" IT system introduction. A traditional introduction project consists of a Planning Phase, an Implementation Phase and finally a Use Phase. In order to fully understand and design PLM systems for use in a real industrial setting, the way they are planned for, introduced, and used is essential. This is why the introduction and planning of PLM systems are essential for this thesis.

Regarding the PLM systems' ability to support management of cross-discipline information, such as mechatronic product data, much remains to be done. The increased complexity of mechatronic development, in comparison to traditional mechanical development, requires information management systems where data management functionality – such as change management and configuration management – applies not only to one specific discipline, but across disciplines and enterprises. It is, however, more than a technical challenge: organisations and development processes have to be considered in order to work successfully with mechatronic development.

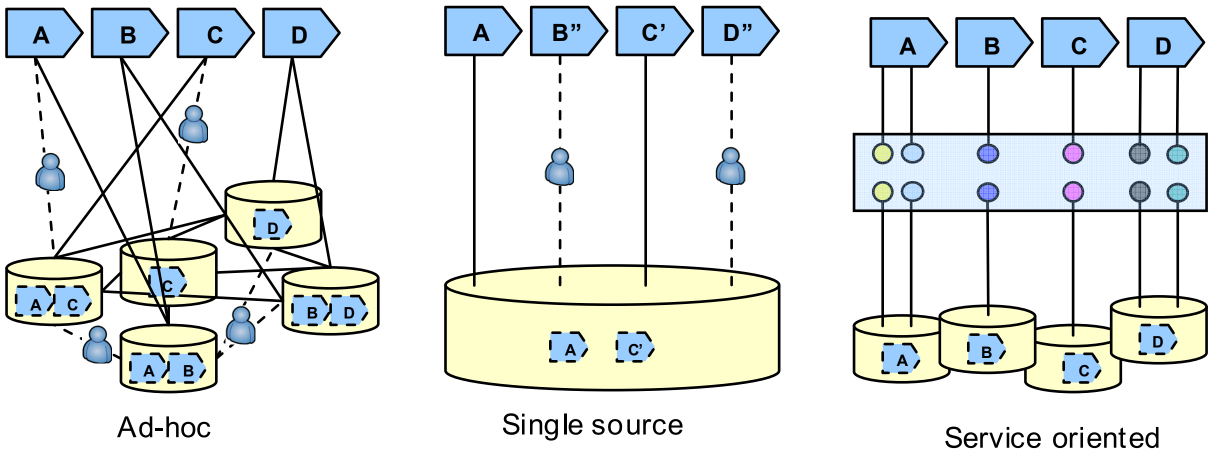


Figure 3. Architectures for Integration (Ćatić et al 2008)

The challenges of integrating PLM systems in mechatronic product development have many dimensions. On the one hand, the business perspective has to be considered, with what is best for the business, the business driving processes, the product, and being motivated by profits and competitiveness as strategic investments. Another dimension concerns the user perspective, the design engineers' ability to work efficiently, and the support from IT tools and systems that they need in order to be efficient, innovative and satisfied with their working conditions. As a combination of the business and user perspective, one can talk about organisational change management. This is of utmost importance in order to identify drivers for change and improvement addressing and involving the different business layers. The third dimension to consider is the technical possibility of designing cost-effective IT systems that can support both the business and user perspectives. Commercial off-the-shelf products or customised solutions have to be considered from the perspectives of both the user and the investment cost imposed on the business. It has not yet been shown in industry or research how to successfully integrate mechatronic development in PLM systems.

1.2 Purpose and Goals of the Research Project

This project has been a part of the Vinnova project "Integrated development of embedded systems" and the ProViking project "Requirement-driven product platform development". The project has also been funded by Vinnova's V-ICT programme and by NFFP. Human aspects and design aspects of an integrated approach to information management in PLM systems are to be investigated, both from an architectural standpoint and from a user standpoint. The purpose is to enhance PLM systems to support hardware and software development and collaboration in distributed, knowledge-rich product development environments. Integrated IT system solutions will help distributed development teams, in which hardware and software engineers work together, to get a mutual understanding of the tasks and roles involved, and thereby to ease collaboration and increase development efficiency.

The goals have been to:

- Investigate differences and similarities between mechatronic disciplines (software, electronics and mechanical engineering) regarding their view of PLM, from a user and a management perspective.
- Evaluate the possibility of mechatronic product data integration in commercial off-the-shelf PDM systems.
- Evaluate and test architectures for how to achieve mechatronic product data integration in PLM systems.

- Evaluate the possibilities with a loose integration concept such as is offered by a service-oriented PLM architecture.
- Develop tools to better manage the user perspective of a PLM system introduction, i.e. to find drivers and facilitators for organisational change management towards better PLM.
- Develop tools to better manage the user perspective of PLM and to assess and prioritise improvement of the PLM system.

1.3 Research Questions

The purpose of the research project, and the identified needs of industry, have been narrowed down to the following research questions:

RQ 1. *How can PLM systems be adapted to better support mechatronic product development?*

In order to answer this question, the current support for product development in the industry today has to be investigated, as well as identifying unfulfilled needs. The mechatronic focus implies the development of advanced multi-technology products, i.e. not purely mechanical or software-based products. Possibly the need of PLM for a development or manufacturing company that only specifies requirements on software, which is then coded by a sub-contractor, differs from what is needed by a company that does complete software development. Finally, the question aims at finding out how customisations or changes in PLM systems can be made in order to give better support for mechatronic product development. This question is oriented towards Papers A, B, C and D.

RQ 2. *Which are the architectural needs of integrating IT systems and tools used in mechatronic product development?*

This question addresses the needs of the domains of mechanical, electronic/electrical and software engineering independently, as well as their need for integration and collaboration across disciplines. The architectural need means that the design of the underlying technologies and hierarchies for communication between central IT systems and disciplinary IT tools and how these communicate with each other is investigated. This question is oriented towards Papers A, B, C and D.

RQ 3. *What are the organisational aspects, focusing on user and management view, of PLM system support and PLM introductions?*

This question aims at identifying benefits and possible disadvantages with an integrated PLM system regarding the actual design work. The research question focuses on organisational aspects and in particular organisational change in the context of a PLM introduction project. It is often not an easy task to perform a large organisational change project that involves many people, processes and IT systems. For example, it would be beneficial to know which impacts could arise from changes in a domain's specific development process, tools, and systems. Further, the research question aims to find conflicting requirements (within the domains, presumptive users, IT suppliers etc.) on a PLM system, which then could be managed. Further organisational change management and PLM introduction concepts will be elaborated upon. This question is oriented towards Papers E and F.

RQ 4. *Could management methods and tools that take in the user perspective support the introduction and the improvement of a PLM system?*

This question aims at answering whether it is possible to attain quantitative and measurable goals that actually help to identify the user requirements on a PLM solution. These tools should help the organisation towards prioritizing and identifying targets for improvements. The tools could then be used to identify processes and IT systems that could be targeted for improvement. This question is oriented towards Papers E, F, G and H.

1.4 Delimitations

- Even though PLM considers the whole lifecycle of the product, the focus in this work is on the development phases. Hence production and aftermarket disciplines are not specifically discussed.
- The focus is on engineering information management and PDM systems, not on information authoring tools such as CAD and other IT systems that cannot be connected to the engineering information management domain.

1.5 Outline of the Thesis

Chapter 1 introduces the reader to the subject and presents the scope of the research including the purpose, goals, and the research questions.

Chapter 2 describes the scientific approach, including an introduction to available research methodologies within design research, as well as an explanation of what approaches have been used. The studies are presented in connection with the papers written and the approaches used in the studies are described and motivated.

Chapter 3 contains the theoretical framework, as well as how this research is positioned with respect to related research. The related research focuses on issues relevant for mechatronic PLM and PLM system introductions.

Chapter 4 is a compilation of the appended papers. The main research results from the separate papers are presented, including the most important Figures and conclusions of each paper.

Chapter 5 analyses the results from Chapter 4, as well as related research, the research approach and the research questions.

Chapter 6 presents the validation approach of the studies and the research results.

Chapter 7 presents the major conclusions drawn from the studies.

Chapter 8 speculates about future studies to be performed, and about remaining research gaps.

2 SCIENTIFIC APPROACH

This chapter presents and discusses the research methodology adopted during the research.

2.1 Design Theory Methodology and Challenges

It is very difficult to understand the data that have been collected empirically or logically if you have not reflected over the chosen paradigms and viewpoints that inevitably are going to affect your research (Arbnor and Bjerke 1994). This research, originated from design science, has its own paradigms and viewpoints, but is also unique within this frame of design science. The research in design science is based on the research traditions of the academic university department and its strong relation to mechanical engineering. The research is related to the engineering discipline, which means that there is an influence of different perspectives including ever-evolving social and technical patterns. Thus, controlled experiments including isolated factors, as in pure natural science, are in principle impossible to perform. Design science has strong roots in mechanical engineering and is often associated with the works of Hubka and Eder (1988) and Pahl and Beitz (1996). These traditions have made design research a structured and process-focused research field with many links to mechanical engineering and product development itself, for example the design research methodology (DRM) described by Blessing (2002). However, research within PLM and engineering information management is not strictly connected to mechanical engineering but borders on many other fields, not least organisational theory and computer science. Rangan et al. (2005) state that research regarding PLM, and in particular introductions of PLM, falls somewhere between sociology and human psychology and is not explored by the current research community.

There are several applicable methods and models available for conducting research in the field of design engineering. When performing research in the area of information systems and computer tools, the model by Duffy and Andreasen (Figure 4) is applicable in order to break down problems (Duffy and Andreasen 1995). The process focuses on phenomena models that are based upon observations and analysis of the reality of design. As a basis for these phenomena models, information models can be designed. In the final step, computer tools can be developed on the basis of the information models derived. In an approach to verify the developed models, they can be tested by moving from the right to the left. The challenge is to identify a problem in reality and systematically, step by step, break it down in order to create computer models/tools that will support the design reality. This is, as pointed out, a structural method that is suitable to apply when developing or structurally investigating the need and solutions for a new engineering support tool. In this research, phenomena models, information models, and computer models/tools are all useful. However, in my viewpoint this model is not directly applicable when working with huge information management systems and organisations where the problem can be dependent on a large variety of unknown factors. In this type of research, more flexible and pragmatic approaches need to be incorporated in order to improve the working situation, rather than solving a discovered problem. There is nothing in the process model that forbids iterations and jumps back and forth, but when doing this repeatedly it is more convenient not to structure the work as a static process, but rather as iterations at different levels of abstraction.

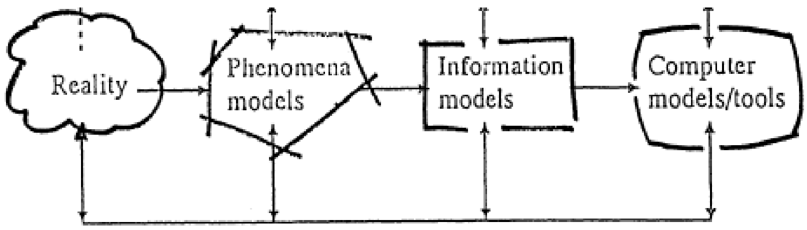


Figure 4. Design Research Methodology (Duffy and Andreasen 1995)

The design research methodology (DRM) described by Blessing (2002) is based on four steps which can then be repeated as the research matures (Figure 5). The method is similar to the Duffy and Andreasen model, in that it is a process with several steps in order to extract and mature a specific result. The method calls for defining a measurable criterion and then continuing by performing a descriptive study and prescriptive studies in iteration, where the last steps are ways to gain feedback from the initial steps. As is often the purpose of processes in industry, it can be used to communicate a flow of events within the research. Each Paper appended in this thesis has therefore been assigned to a specific step in the research process, where it suits best.

Both models (DRM, and Duffy and Andreasen) are based on the notion that there is a reality "out there" which needs to be described and modelled in different stages in order to be understandable for the researcher, and then finally solved by a prescriptive method or a computer tool. Both models are thus based on the analytical perspectives of research. The analytical viewpoint, and hence also design research, has a strong connection to logical empiricism and traditional research within the field of natural science. From my perspective, a system view of research is relevant due to the influences of social sciences and psychology on PLM research. The ability to cluster contributing factors into systems facilitates the analysis where many unknown factors are involved, for example when performing interview studies with a very limited number of interviewees compared to the whole population (employees at a company, all designers, and all humans). The viewpoint of each individual and his/her contribution to the legacy of IT systems that have been built up during years of experience, gained knowledge, and trial and error, is also to some degree relevant for the research field.

When the papers are mapped towards the DRM model, the papers can be mapped towards different levels. Papers B and C are basically descriptive studies; Paper E also to some extent belongs to this group. Papers A, E, and F are mainly prescriptive studies based on the problems described in Papers B and C. Finally Papers D, G and H all show applications of the research, including methods and demonstrators applied to an industrial context. The DRM can therefore be used to map the relationships and dependencies of the papers (and Studies) which are further described in this chapter.

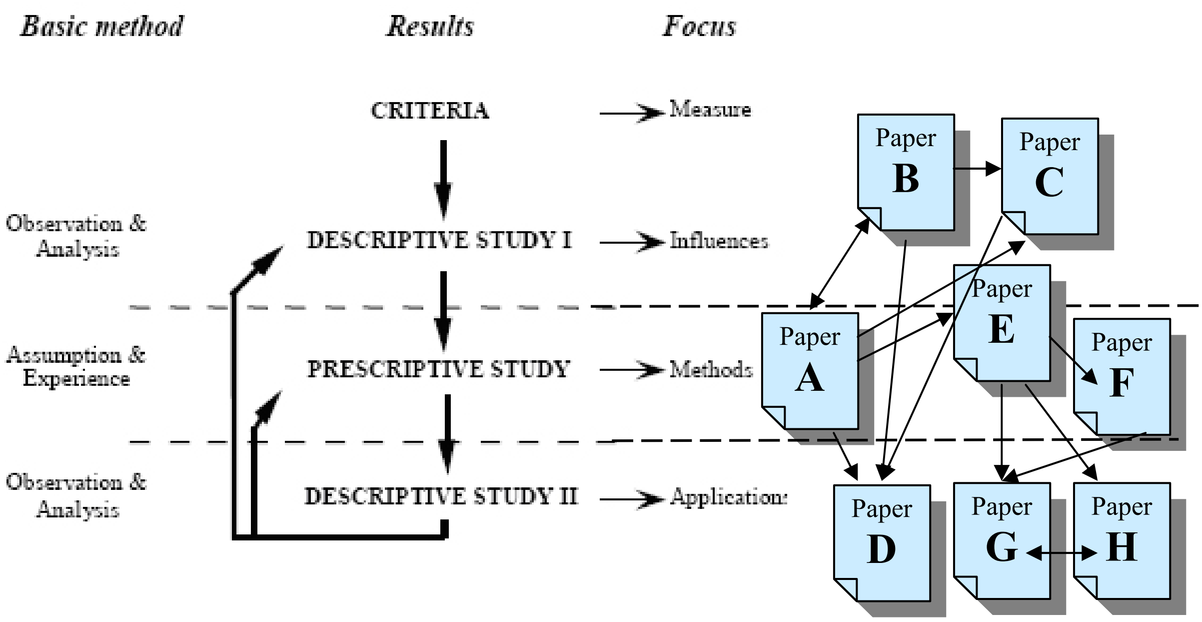


Figure 5. Design Research Methodology (DRM)(Blessing 2002)

2.2 Applied Research Methodology

The applied research methodology is essentially based on a qualitative approach (Robson 2002) employing interviews, combined with quantitative data collection, workshops, document studies, and demonstrator development.

The applied research methodology has been divided according to five different studies performed under the PLM umbrella according to Table 1. From an overall perspective, this research has had the theme of PLM with a specific focus on mechatronic development. This can be broken down into two smaller themes that have coloured this research. The first theme is the architectural theme, where PLM has been regarded from an IT system and integration perspective (Studies 1, 2 and 4), that is, a perspective where technical prerequisites meet the business requirements. The second theme of this research has been focusing more on the human aspects of offering integrated IT solutions in product development, as well as organisational change and improvement regarding PLM implementation. This involves user studies, introduction studies, and interviews with management and specialists (Studies 3 and 5). This is shown in Figure 6 where the different research focuses are mapped towards the studies and the resulting papers.

The choice of having two different themes for the research is connected with the identified research gap regarding planning of and improvement of PLM. From one perspective, the planning of the roll-out calls for structured and well-thought-through maps of the PLM landscape, that is, the PLM architecture. On the other hand, the organisation needs to be prepared, resulting in organisational change management and the human factors. In combination, the PLM architecture and organisation study complement each other and contribute to a purposeful PLM system that will suit an ever-changing organisation.

The character of the studies that are the foundation of this thesis is stated in Table 1. The research approach and research questions, as well as the papers they are reported in, are stated there. One main research question is mapped to each of the papers, but since the papers discuss other questions, these secondary research questions are placed within brackets.

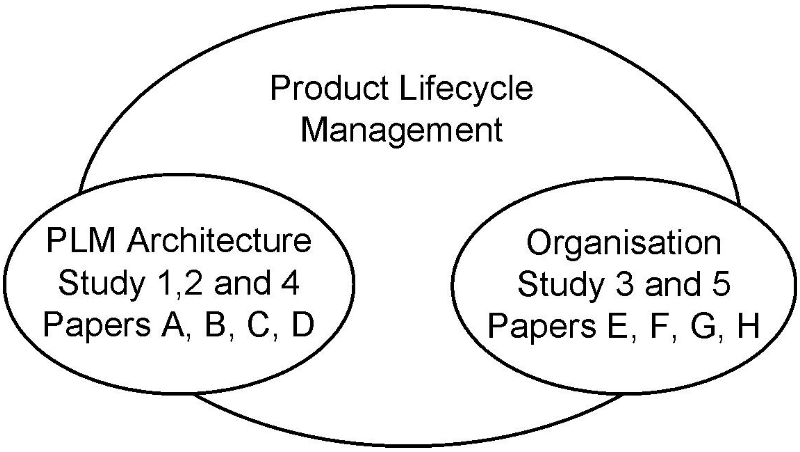


Figure 6. Focus of the Research

Table 1: Overview of studies, papers and research questions

Study	**1**	**2**	**3**	**4**	**5**
RQ	1 (2, 3)	2 (3)	1, 3, (4)	1, 2 (3)	4 (3)
Purpose	To investigate and demonstrate the possibilities with an integrated architecture and information model	Discuss PLM architectures for cross-discipline engineering design	To identify information management strategies	Implementing and testing a loose integration PLM architecture	Identifying measurements for introductions and continuous improvements of PLM
Inspiration		A direct continuation of Study 1	Based on Study 1 and (Bergsjö and Malvius 2006)	Based on Studies 1 and 2.	A continuation of Study 3
Data Collection	Project documentation Interviews Demonstrator	3 Workshops	25 interviews 2 Workshops	Interviews Project documentation Demonstrator	300+ Questionnaire respondents 2 workshops
Interviewees	PLM Specialists	Designers and PLM Specialists	Top and middle managers, designers	Designers Specialists	Designers Managers Specialists Administrative
Studied industry and departments	Automotive and Electronic companies Mechanics, electronics and software, IT	Automotive companies Mechanics, electronics and software, IT	Automotive company Mechanics, electronics, and software	Automotive company Mechanics, electronics, and software	Automotive company Electronics and software
Time Period	2005-2006	Jan 2007	Aug 2006 – Jan 2007	2007-2008	2006-2008
Published in	Papers A, B	Paper C	Papers E, F	Paper D	Papers G, H

2.2.1 Study 1

The research approach Study 1, applied in Papers A and C, is shown in Figure 7, which illustrates the inputs and the outputs of the research project in the three different stages of the research. The study was carried out in collaboration with Mikael Ström from IVF between May 2005 and August 2006. The first step was to analyse the product information management needs at the two firms, and to align their company-specific information models with a generic product lifecycle information model developed from Collier (1999) and Andersson et al. (2002). Data were collected through interviews, workshops, studies of product documentation and use of existing PDM systems at the companies. Interviews and meetings have been the main source of data collection. In all, 25 people have participated in interviews lasting on average for two hours. The workshops, typically with five to eight people present, functioned as forums for feedback and discussion of alternative solutions for the demonstrators.

The resulting information models were the main input to the next step (Paper A): the development of two demonstrators. The main reason for developing the demonstrators was that a demonstrator would make it easier to understand how the information was supposed to flow, how changes can be performed, and how to connect information elements. In comparison with a PowerPoint presentation or information model on paper, a functional demonstrator makes it possible to show the actual engineers how their work can be improved, as well as to identify the limitations of a proposed solution. Earlier, both companies had found it difficult to communicate PLM needs and opportunities, resulting in time-consuming investigation and implementation processes, as well as scepticism from the engineers regarding the systems' potential to improve the work procedures. Two commercial IT systems, one marketed to large companies (referred to as the advanced PDM system in Paper C), and one primarily marketed to smaller companies (the basic PDM system), were used. A number of iterations were made in the implementation process, resulting in a better understanding of user needs from the researcher's point of view, as well as a better understanding of PLM capabilities and limitations from the user perspective.

Finally, the functionality of the demonstrators was tested through demonstrations for engineers, individually as well as in workshops.

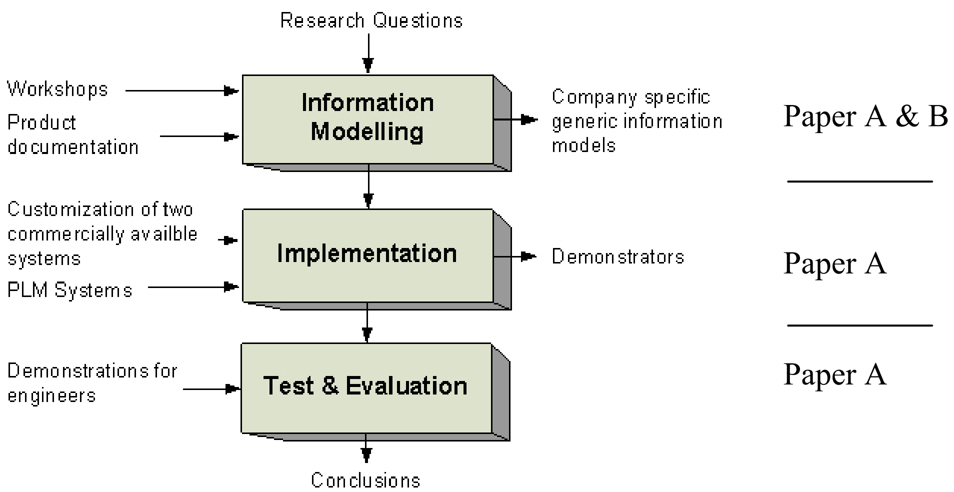


Figure 7. Research approach used in Study 1. Input-output horizontal and research progress vertically.

2.2.2 Study 2

Study 2, whose published result is Paper C, was conducted mainly in collaboration with Dr. Michael Vielhaber from Daimler AG. The background of the Paper consisted of similarities encountered in introducing and customising PLM systems. There was a workshop held at Chalmers in January 2007 with eight participants from automotive companies in close proximity to Göteborg, discussing PLM strategies of the three represented automotive companies. The participants have backgrounds in automotive PLM. The Paper and the workshop focused on discussions related to CM and ECM, as well as alternative PLM architectures and how well they fulfil the CM and ECM concepts. The paper was a result of this workshop in combination with previous work, mainly Papers A, C and Vielhaber et al. (2006).

2.2.3 Study 3

Papers E and F were written in collaboration with Diana Malvius from the Royal Institute of Technology (KTH) in Stockholm, Sweden. Study 3 also included the participation of Sara Molneryd from KTH. The case study was performed at a Swedish automotive firm, and followed an internal project that aimed at exploring and analysing the planning phase of a requirement management (RM) tool introduction. The RM tool was supposed to manage mechatronic product information in EE development.

A participant observation study (Robson 2002) was conducted by one of the researchers who was involved and worked closely for five months with the company. The researcher followed and participated in the project team meetings and was situated on site on average four days a week from August 2006 to January 2007. The field notes that formed the data collection were analysed and verified through arranged workshops with company employees. As an integrated part of this study, 25 semi-structured interviews were conducted to further map the organizational needs. Future users of the RM tool were interviewed, including eleven managers and ten designers from the EE department. Respondents were chosen so that all divisions and levels within the EE organization were represented, spanning from designers to the manager of the EE department. An additional four interviews, focusing on a recent CAD and PDM introduction project, were performed with designers from mechanical engineering. The four interviews in the mechanical department were made with members from the planning group of the introduction project. The interviewees were selected based on recommendations from contact persons belonging to the RM introduction project. The interviews lasted one hour on average and were conducted in August to December 2006.

For Paper E, an addition of two PLM experts involved in global PLM projects within the company were included in the interview group, due to their knowledge and experience about earlier and current company initiatives within the PLM area. One of the PLM experts had more than 30 years of experience from PLM, PDM and IT support for product development. The applied research process consisting of three main steps – findings, analysis and evaluation – is described in Figure 8.

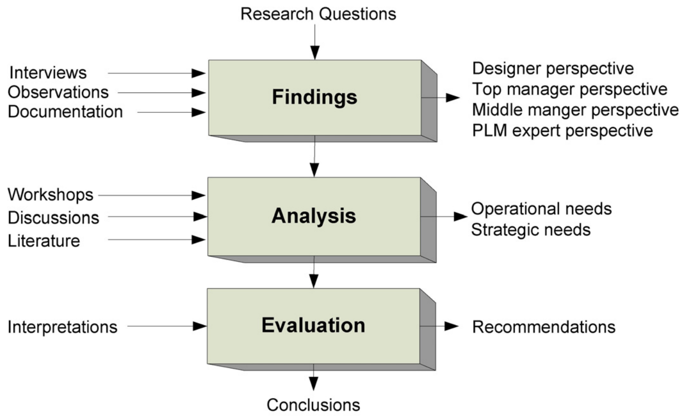


Figure 8. Applied research process in study 3.

2.2.4 Study 4

Study 4 was conducted together with Amer Ćatić as my main research partner. This study focused on PLM architecture and also the integration of Knowledge Based Engineering (KBE) applications within this framework. Previous work within this context includes Papers A, C and Ćatić and Malmqvist (2007). With this work as a basis, it was decided that the framework for this architecture and integration study would be a SOA. An extensive literature (and Internet) search for different ways to realise service-oriented PLM architecture was conducted in order to find other implementations and standards which could be applicable to the study. The concept for the demonstrator was discussed within a group consisting of two university researchers, two master thesis students from computer science, and a SOA expert from the participating company. The general idea was that the study should demonstrate the implications of service-oriented PLM, from a business and a user point of view. In order to make the demonstrator as realistic as possible, it was decided to use an industrial case addressing existing challenges with PLM architecture and integration.

2.2.5 Study 5

The aim of this study was to quantitatively verify previous results described in Study 3. The identification of improvement areas as well as the identification of users with similar needs was the target of the study. Respondents to the questionnaire included employees at the EE and Software development department, including designers, management, and administrative personnel. The questionnaire was sent to 419 unique email addresses. The assumption of the study is that the design engineer is in the centre of product development and therefore is able to give good estimations of the current status of the IS/IT and process domain of the company. This approach to collecting information is showed in Figure 9.

For Paper G, a Partial Least Squares (PLS) analysis was chosen as the multivariate technique to use, since it has been shown to discover cause-effect relationships between different variables. An application called Smart-PLS (Ringle et al. 2005) was used to perform the analysis required. The chosen multivariable technique allowed testing and further refinement of the model. In all 281 (67 %) employees answered the questionnaire.

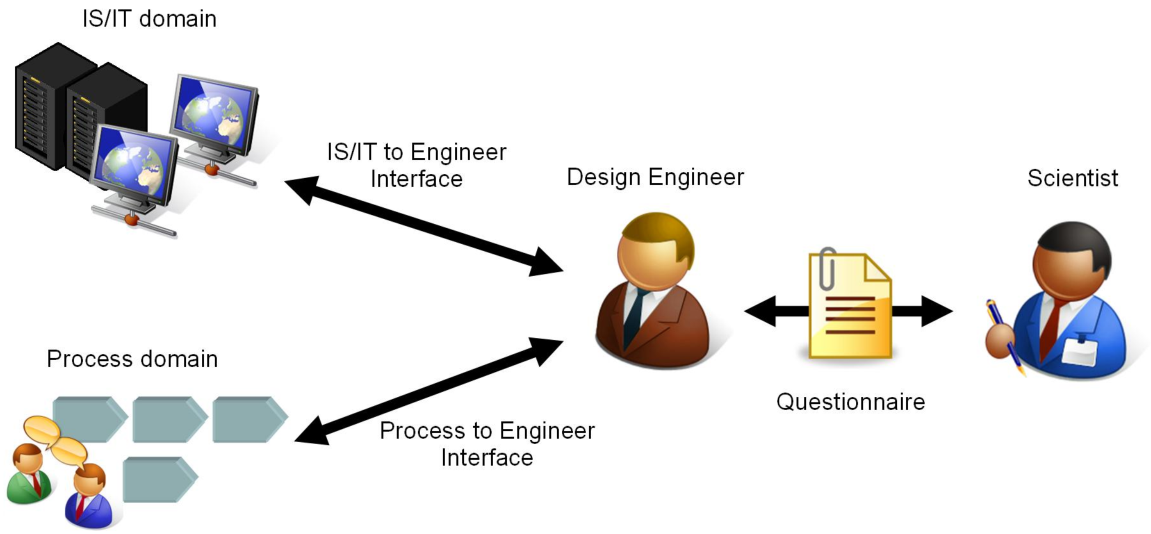


Figure 9. The Design Engineer is the key in order to measure the process and IS/IT domains.

In Paper H, cluster analysis was used as the main analysis method. Here the scope was to find different clusters of IS/IT users. Six questions were related to user satisfaction, four concerned expectations, and another four concerned benefits achievable with ICT. For this analysis 312 out of 419 (74%) IT/IS users could be used from the data material and be clustered according to the cluster analysis performed in SPSS v. 13 (SPSS 2008).

2.3 Approach to Validation of the Results

The model of Duffy and Andreasen shows the challenge of studying reality and creating models of reality. The challenge is that, if the steps of moving from reality to computer tools and back are not consistent, the consequence may be that the solution does not correspond to the reality, i.e. the real need. It is therefore important that the research is validated to ensure that the correct problems are solved. This can be done by applying (testing) the computer tools or models in a design reality. Design science is not an exact research field that can be quantitatively validated by experiments, as in mathematics and physics. Findings from real-life development projects are difficult or even irrelevant to validate through mathematical models, due to the large complexity and number of variables affecting the result (Almefelt 2005).

According to Buur (1990) there remain two major ways of verifying the validity of a design research study: logical verification (i.e. that the research results are based on related research and that there do not exist any contradictions with accepted theories and methods) and verification by acceptance (i.e. that the research is acceptable/adopted to/by experienced practitioners within the scope of the research). Validating a design method also calls for evaluation of its purpose by demonstrating its usefulness (Pedersen et al. 2000). Pedersen et al. (2000) further present an approach to validate design methods. It is believed that this method also is applicable for this research work. The validation square (Figure 10) contains four views, in order to address the aspects relevant for validation purposes. The four views are elaborated with the empirical and theoretical dimensions as well as the structural and the performance dimensions. The performance variables can be connected to the efficiency of the method developed, i.e. the ability of the method to perform what it is intended for. This validation is best done with a quantitative evaluation of the method. The structural dimension of the validation square is more related to effectiveness, and is best validated by qualitative evaluation (Pedersen et al. 2000).

There are several foundations that PLM research is based on. It has its foundation in areas from organisation theory to computer science. In order to ensure the theoretical validity, the research work has to reflect upon these areas and explain possible deviations from these fields. The studies must focus on areas where PLM is applicable and useful. Studies carried out at large vehicle manufacturers and especially within the development of electrical and electronic systems are believed to fulfil this requirement. The combination of quantitative and qualitative evaluation of the research results will also help in validating both the structural and the performance dimensions of the research.

These views can be related to research in PLM according to the following:

- **Theoretical structural validity:** Correctness of constructs, both separately and integrated. E.g. consistency of theory in phenomena modelling, similarities and applicability to mechatronic product data representation.
- **Empirical structural validity:** Appropriateness of example problems (case studies) and the usefulness of the method applied. E.g. industrial projects where highly advanced mechatronic product development can be studied.
- **Empirical performance validity:** Performance of the solutions with respect to the example problems. E.g. the measured performance according to fewer errors (higher information accuracy), reduced lead time in product development.
- **Theoretical performance validity:** Performance of the method beyond the example solutions. E.g. transferability of the specific case to other cases. Systems engineering in the automotive industry in general, applicability to other industries.

To some extent it is possible to use logical verification regarding the demonstrator developed, by asking the question: Is it possible to implement functions and concepts in the PLM systems? However, for applicability and for the need and use of the research results in industry, verification by acceptance is a reasonable method. Verification by acceptance can be done by presenting, demonstrating, and possibly implementing the IT system in a design reality, and discussing the problems and solutions with representatives from the industry, interviewees, and research colleagues.

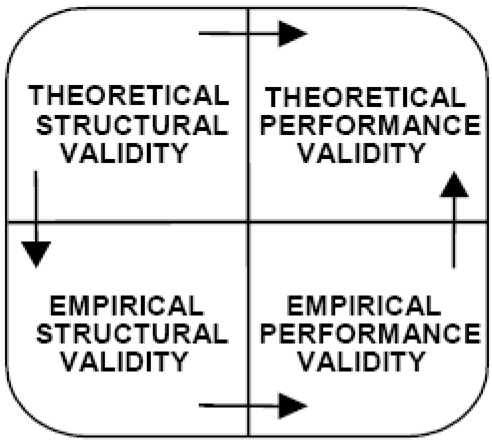


Figure 10. The validation square (Pedersen et al. 2000)

3 Frame of Reference

In this chapter the underlying theories and neighbouring subjects that will support the research are presented. Chapter 3.1 serves as an introduction to the field of PLM for mechatronic integration, which is further explored in the subsequent sections.

3.1 The Field of PLM for Mechatronic Engineering

There are several research areas that are important to investigate when doing research in PLM. The PLM system is meant to work as the hub for product development systems and tools, increasing reliability and facilitating exchange of product data. Support for mechatronic development is essential in industry, especially in the automotive and aerospace industries as more and more functions are realised by the use of software (CIMdata 2005). Since the information management system itself involves the whole company, organisational and process-related areas are of importance. Work procedures, supporting tools and information management have to be considered in order to work integrated in product development (Norell 1992).

The PLM information is often a compilation of several heterogeneous systems that are used in mechatronic development, and makes it necessary to perform changes and design alternative processes in order to work (Svensson 2003). Since the mechatronic area involves many disciplines within a company, the prerequisite of creating transparent information that can be interpreted by several engineering tools across the company is vital. Neighbouring areas in relation to the research field (Figure 11) are introduced in the following passages.

The area of design theory contains work on how to develop products successfully (e.g. Pahl and Beitz 1996; Ulrich and Eppinger 2004). This is relevant to PLM research since the PLM systems themselves must support the way engineers work. Processes within the PLM system must be adaptable to the prerequisites of companies, and to ensuring the integrity of the information.

Standards have been developed in industry to facilitate collaboration within and between companies. Related to the field of PLM is the STEP (Standard for Exchange of Product Data) standard developed by ISO to facilitate the exchange of product data. Also the Object Management Group (OMG) standards for software modelling, such as UML and the newly developed SysML, have shown their applicability to modelling systems, information, and processes used in PLM systems. Also standards for communication within a PLM system or between suppliers are applicable, e.g. OASIS standard and OMG PLM Services standard.

Mechatronics is a multi-technology field that mainly comprises electrical and electronics (EE), mechanical, and software development. The diversity in development processes and tool support of these fields makes it very complex to truly perform mechatronic information integration. PLM research, within the field of mechatronics, especially focuses on the integration between SCM and PDM systems (Svensson 2003; Persson-Dahlqvist 2005), i.e. integration on the database layer rather than on the engineering tool layer. Such system integrations are believed to make it easier to collaborate around product data.

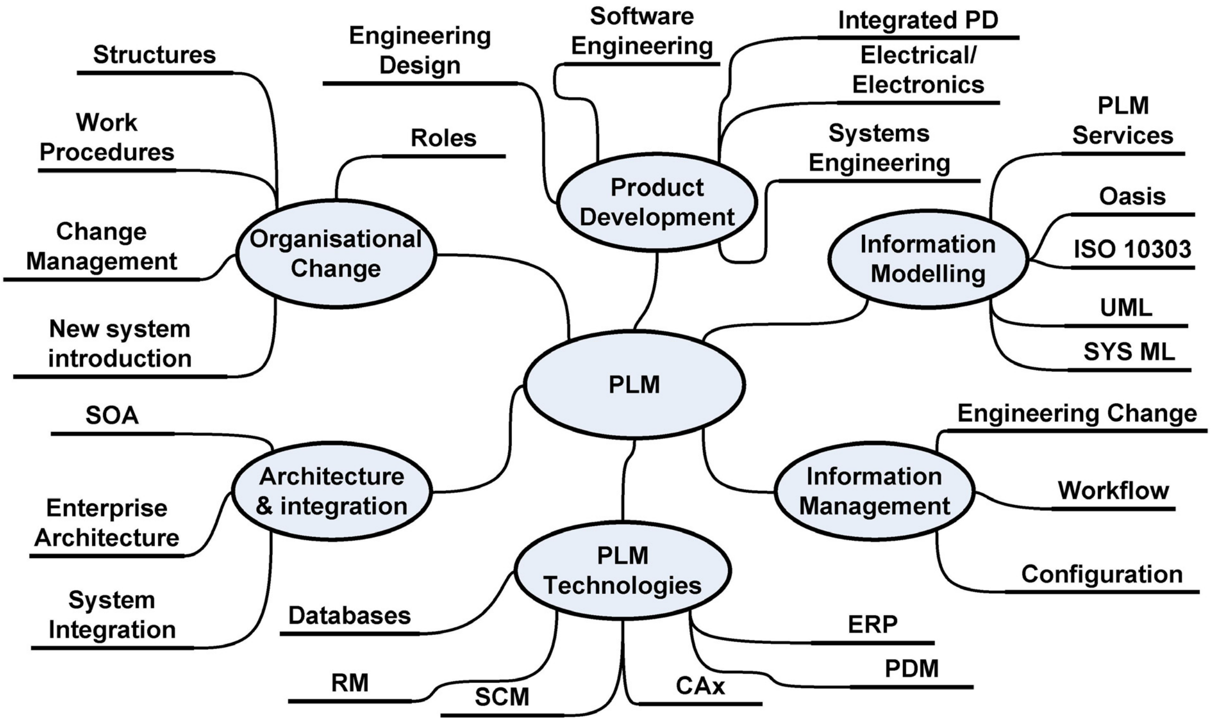


Figure 11. The PLM research area. The fields correspond to the chapters and contents of this chapter, starting with Product Development section 3.2, and ending with Organisational Change section 3.7

Under the PLM umbrella, several engineering tools and information management systems are included both for managing and for authoring product data. Requirement management (RM), PDM, and CAx are only a few of these. In the scope of this project, IT tools and systems regarding the mechatronic field are of interest to monitor. Traditionally, the integration between CAD and PDM has been an area of research. This area has, however, matured and the research has now continued into other areas such as mechatronic integration, supplier integration, and complete lifecycle traceability. The biggest concern in this field is believed to be the configuration complexity, and the tractability issues regarding engineering changes (Bergsjö et al. 2007).

Information management concerns all information that is created and managed within and between organisations. For this research it is interesting to know more about workflow and product development processes within an organisation, across disciplines. When computer systems are involved, information is preferably stored in databases, which also constitute a field of research by itself.

Since PLM involves the whole development at large companies, not only technical challenges can be investigated. The organisational and business aspects are also important and there is much research performed in the field of change management, new system introduction, and how this should be done in order to maximise the benefit of the IT system.

According to Svensson (2003), engineering information management (or PLM) can be divided into four views. These are processes, information, organisation, and information systems (Figure 12). The four views are all dependent on each other and changes in one of the views will have impacts in the PLM system as a whole.

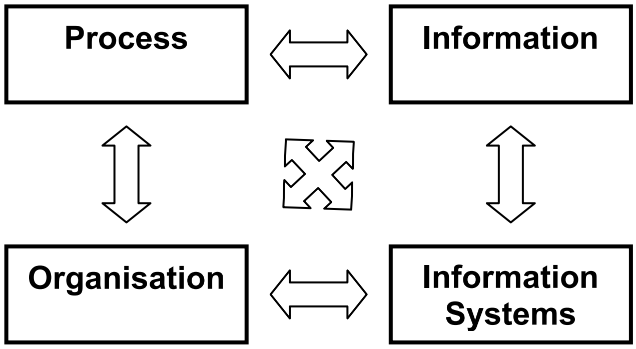


Figure 12. The four views of a PLM system (Svensson 2003)

3.2 Product Development

A product development process is the sequence of steps in which an enterprise designs and commercialises a product, beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product (Ulrich and Eppinger 2004). The steps are intellectual and organisational rather than physical, and are dependent on the creativity of the process participants. Mechatronic product development includes several aspects of product development; not only is the systematic process of generating a product as in Figure 13 needed, but also aspects regarding the use of multiple technologies, and the organisational perspectives of managing product development in large organisations.

3.2.1 Product Development Processes and Methods

There exist several product development methodologies in literature (Pugh 1991; Pahl and Beitz 1996; Ulrich and Eppinger 2004). These are typically focused on the development of products that has its origin in mechanical engineering. The models focus on sequential steps in order to gather the customer needs and narrow them down to a producible product that can be sold on the market. The process according to Ulrich and Eppinger is shown in Figure 13.

In the defence and aerospace industries, another methodology for product development, systems engineering (SE), has been developed where everything is characterised as systems and subsystems. These systems can be described by the use of items, attributes and relations (Blanchard and Fabrycky 1998). The systems engineering process is often shown as a V. The V-model describes the work of allocating and designing to meet requirements on the left side, and verifying them on the right side. Each step in the process corresponds to a refinement of requirements on the left side and integration of subsystems on the right side of the V (VDI-richtlinien 2003).

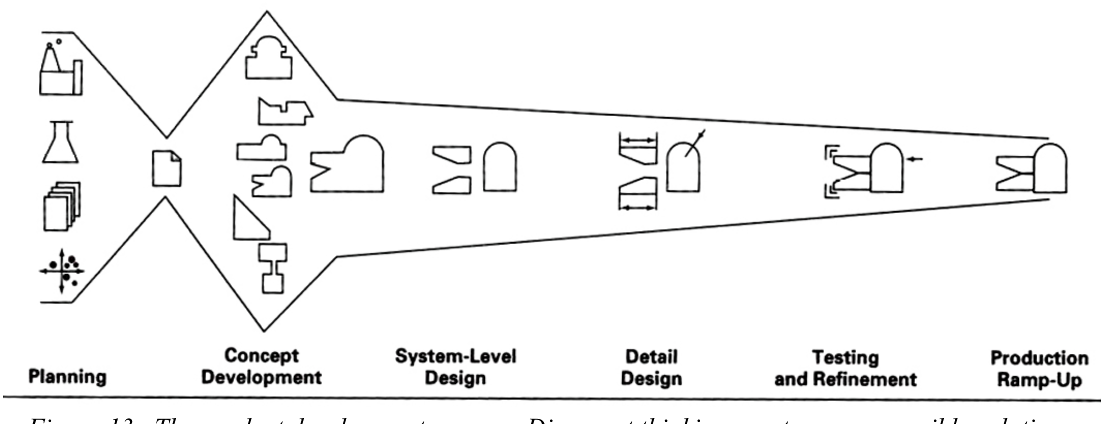


Figure 13. The product development process. Divergent thinking creates many possible solutions, and convergent thinking focuses on one resulting product (Ulrich and Eppinger 2004)

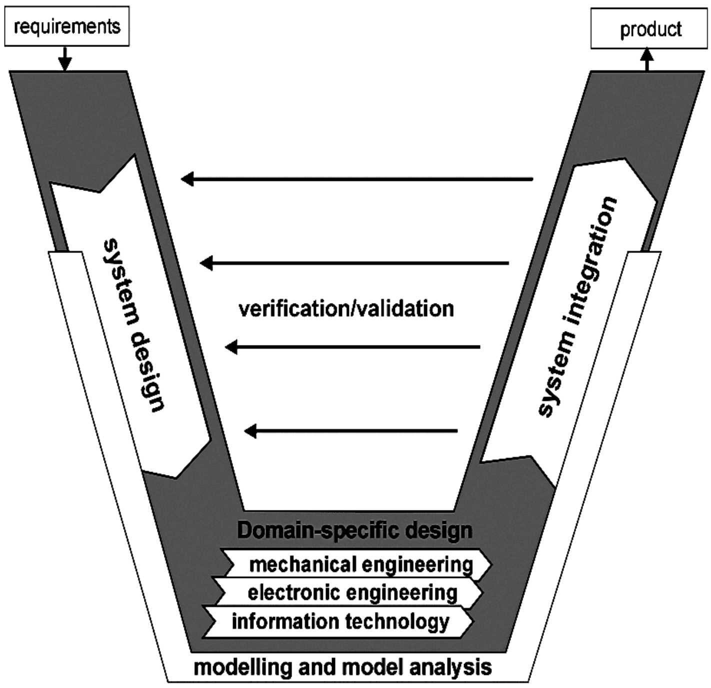


Figure 14. The V-model as drawn in VDI 2206 (VDI-richtlinien 2003)

In the standard VDI 2206, a general guideline for developing mechatronic systems in a V-model approach is described (Figure 14). VDI 2206 is a German effort to standardise and refine a general development process for mechatronic systems. The development starts with a need (requirements) in the left leg. Requirements on systems and subsystems are described in the left leg. In the bottom of the V, the development of domain-specific solutions is performed. In the right leg of the V, the system integration phase makes sure that the product is working as described by feedback to the left leg.

System-Based Product Modelling (Collier 1999) is an approach to linking mechatronic product data to development activities. Figure 15 shows the scope of the process, namely systems integration, design and visualisation, approvals and release planning, and supplier integration and its relation to key information elements.

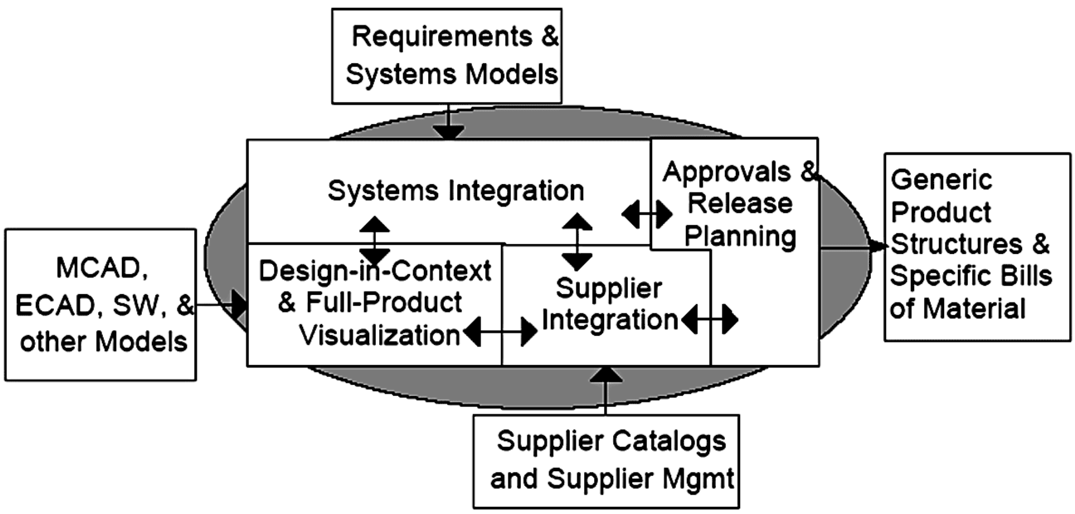


Figure 15. Product synthesis applications benefiting from Systems-Based Product Models (Collier 1999)

3.2.2 Software Engineering

In comparison with the previously described product development methods, software engineering has evolved from a separate field, with its own methods and priorities. Software projects are different from other development projects in several ways (Sommerville 2007). For example, the product is intangible, meaning that there is no physical product, or no physical process except documentation that the project is advancing. There is no standard process defined, and even though there have been large advances in developing a standardised process, it is difficult to predict problems and errors with certainty in a software development process. Software development in large projects is often one of a kind, where previous experience of similar systems is not known. Advances in software engineering are rapid and it is thus difficult to find routines and standardisation in the development. Although there are differences, there is also a great potential for exchange of development concepts between the disciplines (Nambisan and Wilemon 2000). Software engineering is to a high degree iterative, and involves many tests and prototypes during the development process.

The waterfall model (Sommerville 2007) is a process containing several overlapping sequential steps developed specifically for software development. The process is divided as follows: Requirements definition, System and software design, Implementation and testing, Integration and system testing, and Operation and maintenance. These stages overlap and information from the previous step feeds the next step. On this high level, it is similar to development processes in the mechanical discipline. A criticism of this “early” model for software development is that it is inflexible and may have the result that software which does not meet the customer requirements is developed.

The Boehm spiral model (Sommerville 2007) avoids the criticism of the waterfall model since it is more iterative and consistently manages risks. The process is based on a generic model where each development step is represented by a loop (beginning in the centre and travelling outwards (Figure 16).

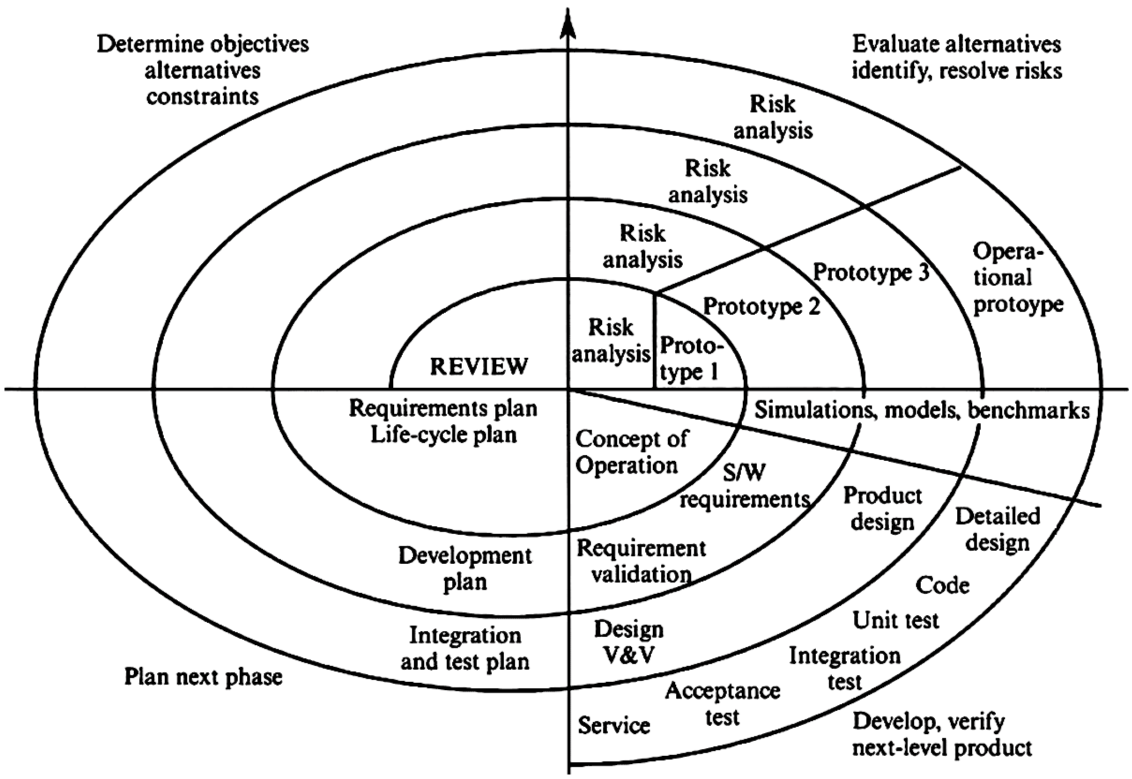


Figure 16. The spiral model (Sommerville 2007)

Differences from general product development models become more visible in the spiral model. The constant development of prototypes, and iterations between requirement management, simulations, benchmarks etc., make it more difficult to align the process with a traditional product development project process.

There are several ways that prototypes are used in software development. An example of prototyping methods is the evolutionary prototyping method (or simply Evolutionary development), where a functional prototype is developed and refined according to customer requirements over time. Other prototyping methods involve throwaway prototyping and incremental prototyping. Prototypes in rapid software development make it possible to quickly assess a software and its behaviour in order to validate or try out a technical solution (Sommerville 2007). The prototype can be used either as a throwaway prototype to model a behaviour, or as a core for the continuation of the development project.

One formalised process that has been developed during recent years is the Rational Unified Process (RUP) (Figure 17). It was developed by Rational Software, which is now a part of IBM. RUP is based on the following concepts (Kruchten 2000):

- *Iterative software development:* Makes it possible to manage risks early in the process, and avoids mistakes in e.g. requirements being discovered early.
- *Requirements management:* Systematic management of requirements helps the development process. Most requirements, except for the most trivial ones, are identified, stated, and changed during the iterative development process.
- *Component-based architecture:* Enables the software architecture to be viewed from several perspectives, based on roles in the software development group. The systems architecture is an important deliverable in order to manage the iterative development.
- *Visual software models:* Modelling helps the development team to visualise, specify, construct and document the structure and behaviour of software systems architecture. UML is a commonly used language for this purpose.
- *Change control:* Manages the changes made during a software project. Releases that are made in the end of each iteration are managed and traced in order to discover errors in future releases of the software system.

A systems engineering approach is highly applicable and used in software engineering projects to manage requirements on computer-based systems (Sommerville 2007). The division of systems and subsystems, and final development of software in parallel with hardware systems (as described in Figure 14), is a solution that enables work with both software requirements and software integration in physical products.

In general, the software development process is possible to synchronise with a mechanical development process (Svensson and Crnkovic 2002). To deal with software integration in detail, two concepts are presented: (a) treat the software as components by managing the executables as such, or (b) treat the software's internal structure as a part of the system developed. The last concept manages not only executable files, but also structural components such as requirements and software structures. This approach would make it possible to perform traceability in the software from software system level down to software components.

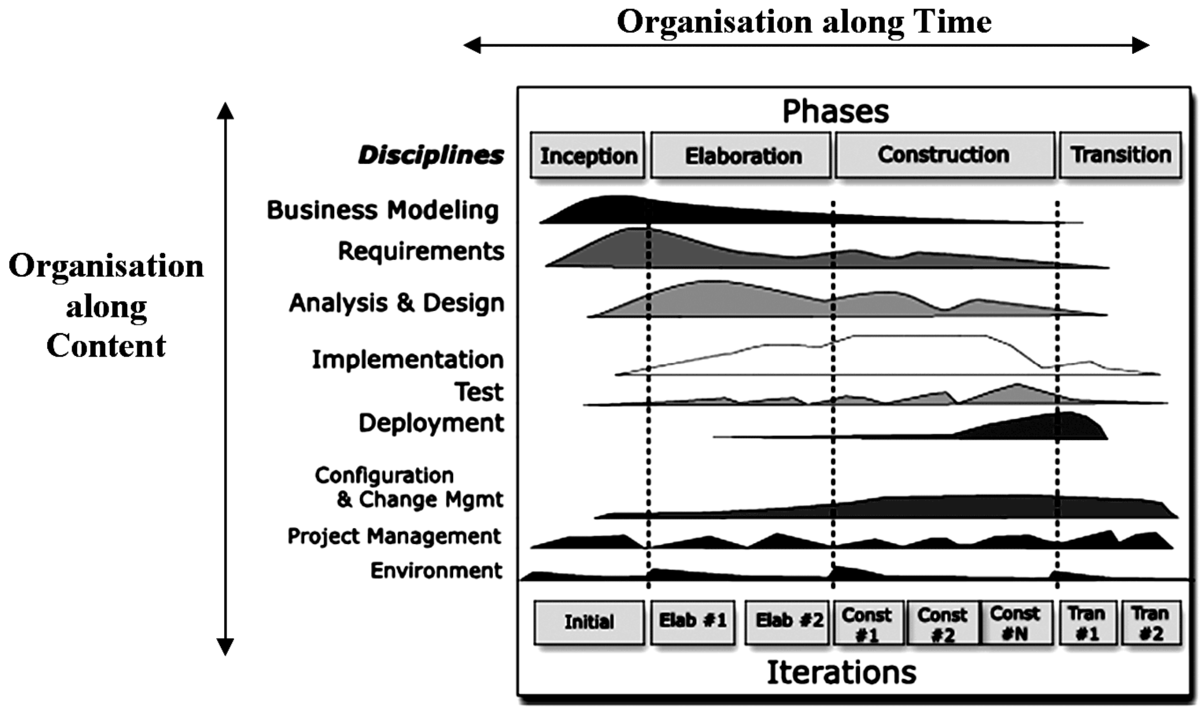


Figure 17. The RUP process (Kruchten 2000)

3.2.3 Areas for Future Research

The development processes for mechanical and software development show great similarities on a higher business level but are not consistent on a lower user level e.g. in the different use of iterations and prototypes. A proposed possibility is to connect these heterogeneous domains together by focusing on the similarities on a higher abstraction level, e.g. the functional level (Zimmerman et al. 2004). This is further elaborated regarding IT systems in Chapter 3.5. Software and physical products are significantly different, and the process and focus of development differ significantly in a way that makes it difficult to integrate their development processes meaningfully. E.g. in software development there is no additional cost but labour to produce prototypes, which makes this a central part of the development – whereas the development of prototypes in the mechanical discipline is not only costly but also time-consuming, with lead times for assembling all the parts. Simulations are becoming more important as the software projects themselves become more complex and involve more programmers. If these software trials could be connected to e.g. digital mock-ups (DMUs), common in mechanical engineering, it would allow simultaneous simulation of both software and mechanical parts. Virtual prototyping involving the complete mechatronic discipline would be possible, as well as simulation of a multitude of states and complete functions.

One question for this research project to pursue is whether it is necessary to change the development process in order to adapt it to PLM systems, or whether it is possible to continue having separate processes but a common information management system. Both ways are technically possible over time, even though large organisational changes tend to take a lot of time in order to be successful. The attempts of e.g. the VDI 2206, and systems engineering in general, to create a common product development methodology for mechatronics are being accepted in industry; also information management system support is showing progress in the area, even though no commercial IT system with complete support for mechatronic development has yet been seen on the market.

3.3 Information Modelling

When working with product development in a highly digitalised environment, plans for how to structure and represent information must be made. The need of information and how that information is transformed during a product development project must be dealt with, as well as connections to the development process and the product during its entire lifecycle. This subject has been investigated in the literature and in several independent standards. When it comes to managing data there are several approaches.

3.3.1 Information Modelling for Mechatronic Products

To describe a primarily mechanical product and how it functions has been the theme of Hubka and Eder (1988). Their Theory of Technical Systems shows how a technical system interacts with a human operator to perform a change from an input to an output. The model has been refined by Andreasen in the Theory of Domains (Andreasen 1991). This thinking is further elaborated in the Chromosome Model (Andreasen 1992). The terminology of the Chromosome Model is applicable for modelling of mechatronic systems, since there is no difference if functions in the Chromosome Model are realised with hardware or software (Hallin et al. 2003).

Property-Driven Development/Design (Figure 18) (Weber et al. 2003) is a theoretical model evolved from the work of Hubka and Eder and of Andreasen. The focus is modelling of a product in a PDM/PLM system. According to the model, there is a distinction between characteristics and properties, where characteristics describe the structure, shape, and material of a product, while the properties describe the product's behaviour. Properties depend on several aspects including the chosen characteristics and cannot, in contrast to characteristics, be determined by the designer. Each expansion of the PLM system (Figure 18) to include more functionality is shown by the boxes outside the core (grey) PDM/PLM system. This extra functionality includes differently detailed dependencies (Dx) between characteristics (Cx) and different types of properties (Px). The model also includes product lifecycle properties (PLj), and means (M) to realise the relations to people, methods, knowledge etc.

System-Based Product Modelling (Collier 1999) is an approach to modelling mechatronic product data in PLM systems. The information model contains the following objects divided into three main areas according to lifecycle stages. These are manufacturing modules, engineering models and product systems. The information model also contains interface objects in order to manage relations between components – models, systems and modules.

An information model based on Collier's model for integrated mechatronic data has been developed by Andersson et al. (2002). The information model contains elements for requirements, functions and properties, as well as physical components such as mechanical, electrical, firmware and software. The objects of the information model are arranged in families and variants that can be connected to either a manufacturing view or a functional view. The information model is described in UML format, and is expressed to include the chain from requirement creation to production. It is also designed so as to comprise several technology domains including software, electronics, and mechanical definitions. The model has not been implemented in industry, but the involvement of both researchers and industry speaks for a realistic approach.

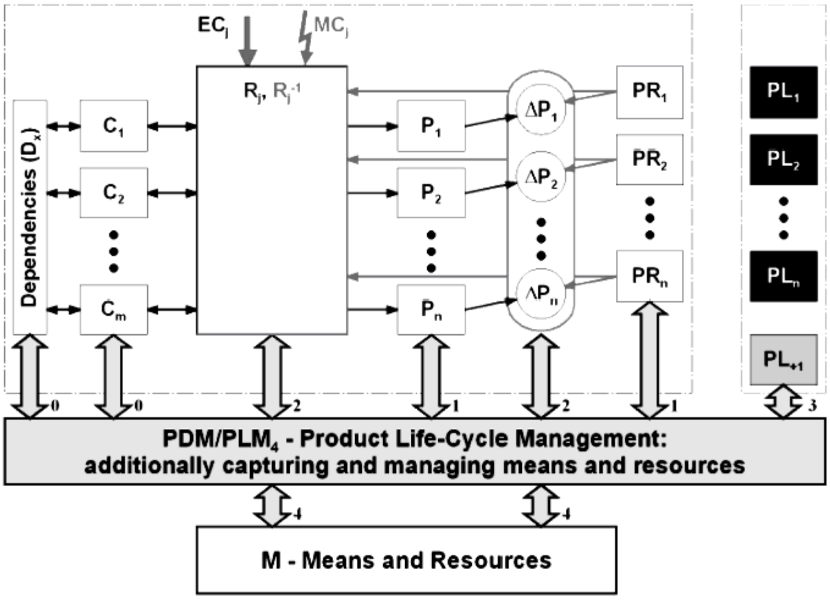


Figure 18. Evolution of PDM/PLM based on Property-Driven Development/Design. (Weber et al. 2003)

The function-behaviour-structure (FBS) framework was described originally by (Gero 1990). The FBS model treats design as a process where functions, behaviours, and structures are essential. The steps are linked together by processes that can be seen as the different stages of design. In Figure 19 there are eight processes linking function (F), expected behaviour (Be), behaviour derived from structure (Bs), structure (S) and design description (D) together. The model can be extended to describe even more processes (Gero and Kannengiesser 2004). The model makes it possible to distinguish between different types of information within the design process. Function information regarding "what it is for" can be used. The model also shows when (in which process) that particular information is usable. There is no particular orientation towards design of mechatronic systems, but the model does not exclude them.

3.3.2 Standards for Modelling Data Exchange

Attempts to standardise information related to PLM systems and mechatronic product development are ongoing. Standardisation projects with connections to this thesis are described in this chapter. There exist two main modelling techniques, Unified Modelling Language (UML) and STEP Express. Both of these techniques, in the most basic sense, illustrate items, attributes, and relations.

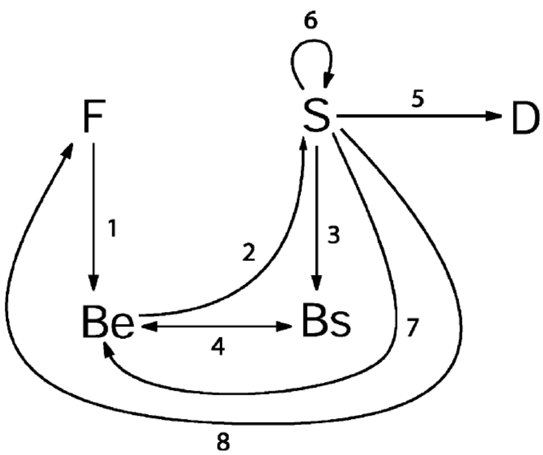


Figure 19. The FBS framework (Gero 1990)

UML

UML is based on three main models: Functional Model, Object Model, and Dynamic Model. The standard is officially defined by the Object Management Group (OMG). In UML 2.0 there exist 13 types of diagrams for different types of information modelling tasks (OMG 2006a). The most common one for information modelling is called the class diagram. In related research it has been shown by (Merlo et al. 2005) that UML can be used as a powerful tool to model information in a way that reduces risks of misinterpreting the models. A model based on UML is easily understood even with no UML experience (Johansson and Detterfelt 2006), which makes the model suitable for communicating product models in large projects involving different engineering disciplines.

SysML is a development of the UML standard to be less software-focused and better manage systems engineering information. Despite the limitations of UML, it is still possible to model complex relations involving both software and mechanical parts in UML diagrams (Johansson and Detterfelt 2006). The standard UML4SysML was finally adopted by OMG in May 2006 (OMG 2006b). The standard is applicable to modelling in systems engineering contexts with a few exceptions, for example storage of items (Bock 2006). Comparisons of SysML to UML advantages for systems engineering can be identified. An example applicable to mechatronic development and modelling of automotive systems is that SysML can use requirement diagrams to capture functional, performance and interface requirements, whereas UML is subject to the limitations of Use Case diagrams to define the functional requirements. The modular approach taken in UML and SysML facilitates implementation in PLM systems.

STEP

ISO 10303 is known as STEP or the Standard for the Exchange of Product model data. The standard contains a number of Application Protocols (AP). These protocols contain adaptations of the ISO standard to certain businesses (Figure 20). It has been shown in related research that STEP is a suitable information model for mechatronic product development. Hallin et al. (2003) showed that AP 214 could be used for this purpose. The applicability of STEP is discussed by (Pratt 2005), e.g. the possibilities to perform configuration management on a single product to be accessible over its lifecycle as in AP-239. This would allow better control over produced products and enable easy software updates, much needed in the automotive industry. Customisation of UML for systems engineering (SysML) is coordinated with ISO STEP AP-233 effort in order to provide a comprehensive framework for the exchange of systems information using standardised notations and semantics (OMG 2007). Express is the language adopted in the ISO standard 10303-11. Express is available both as a text-based and as a graphical specification.

- **Part 210 - Electronic assembly, interconnect and packaging design.** The most complex and sophisticated STEP AP.
- **Part 212 - Electrotechnical design and installation.** Designed as a complement for AP214, but not fully harmonized with it.
- **Part 214 - Core data for automotive mechanical design processes**
- **Part 233 - Systems engineering data representation**
- **Part 239 - Product life cycle support**

Figure 20. List of application protocols within the Step standard 10303, standards related to this research

3.3.3 Areas for Future Research

The information models presented in this chapter (Collier, Weber, Andersson) all show similarities regarding their scope and contents, and should be applicable as a basis for development of a mechatronic model in PLM systems. The scope of the information models is general, and they do not in particular go into details regarding the micro-processes to include the differences of e.g. version management in the mechanical or the software discipline specifically, but tend to focus on the state of practice in the mechanical discipline. The information models, at most, leave room for the company and engineer to comply with the standard by not being too specific.

Recent standardisation efforts have come so far as to standardise a platform for exchangeable software components (Fennel et al. 2006). However, little is said about future management of these standardised components. In PLM research a better understanding of software development is needed, by e.g. testing how well mechanical approaches fulfil software designers' needs and vice versa.

3.4 Information Management

Information management concerns all information that is created and managed within and between organisations. For this research it is interesting to know more about workflow and product development processes within an organisation, across disciplines, when computer systems are involved. Of particular interest to this research and the problems encountered in industry are the processes of Configuration Management (CM) and Engineering Change Management (ECM). (Paper C)

3.4.1 Configuration Management

CM, i.e. the management of both variants and versions of product information, poses special challenges in a multidisciplinary environment. It is a complex process even in a single-domain environment, since there is a large number of both people and components that have to be managed. The design cycle of a complex product forces the design and manufacturing to have a multitude of possible configurations of similar products over time. In mechanical engineering, for instance, parts typically go through a process of several iterations until they reach sufficient maturity to be released. In each prototype built, different versions of the same part may be used. Designers have to be able to manage all different kinds of such configurations to create and validate their designs. With thousands of parts comprising a product, it is obvious how sophisticated the configuration mechanisms must be in order to cope with these needs.

In a multi-domain environment, differences in the product development process between different engineering disciplines are problematic – for example in software and electronics development, different lifecycles, prototyping mechanisms, configuration logics, and data schemes are used than in mechanical development. The total lifecycle for an information appliance is generally less than a year (CIMdata 2006a). Bringing this closer together with the mechanical design domain, in order to e.g. ensure having a correct combination of software version, control unit version, and mechanical part version, both domains' configuration mechanisms have to be enabled to communicate with each other. (Paper C)

3.4.2 Engineering Change Management

ECM is an important part of product development. In order to work with ECM across disciplines, a better way to represent the products would make it possible to enable relationships not limited to geometries, but also to include electronic functions realized by software. It is not a major problem if a PLM system requires some time to create new product information, as long as the information is easy to update. Changes in mechanical parts are relatively few since they are very costly (hard tooling etc.), and it would therefore not matter much if the change process requires some time. However, when it comes to changes in software there could be hundreds of changes to software during a product's lifecycle, which could lead to a lot of administrative work put on the designers.

The key concept when considering ECM is to link all the affected data with an engineering change order. Problems with ECM are related to the lack of proper IT support in current IT systems. This leads to communication problems between different domains, as many functions can be involved in a change (Pikosz and Malmqvist 1998). Huang and Mak (1999) conclude that ECM is a time- and resource-demanding activity and that, depending on the change's extent, it can involve large parts of the company. In one study (Huang et al. 2003), over 80% of the respondents replied that causes of changes can be traced to poor communication and late discovery of problems. Lee et al. (2006) present a list of causes for ECs that, besides poor communication, include careless mistakes, snowballing change (changes due to other changes), cost savings, ease of manufacturing and product performance improvements. Lee et al. argue, however, that ECs are not always unnecessary. Many of them actually are beneficial and ECs should be viewed as inevitable, implying that efforts should be directed towards managing them rather than avoiding them.

In a mechatronic product, both the EE domain and the mechanical engineering domain must be involved, as well as downstream domains such as manufacturing and aftermarket domains. When domain-specific IT systems are introduced, e.g. in the EE domain, these systems will only be able to manage changes in their respective domains, and changes that would affect neighbouring disciplines have to be managed in another disciplinary system. Two major problems have been identified: process redundancy and data integrity (Paper C). Process redundancy is coupled with the need to perform the same type of actions in separated disciplinary systems, while data integrity is connected with the fact that information sometimes has to be duplicated in order to serve each disciplinary system.

3.4.3 Areas for Future Research

CM and ECM are two of the most important building blocks of PLM solutions. New concepts for integration have to be developed in order to transfer the existing single-domain methods to a multi-domain environment. Different approaches for such concepts have been presented in Paper C, and preferences have been pointed out. Initial investigations have shown that the main approaches suggested for CM and ECM are generalizable to support other multidisciplinary situations as well – e.g. multi-domain access right management.

3.5 PLM Technologies: Information Management Systems

There exists a large amount of engineering tools and systems. Some of these are adapted for a very specific task, whereas others try to manage large areas of the product development process. According to CIMData (2008) there exist three types of PLM-related tools and systems. These are the PLM tools for creating information, where mechanical CAD systems are the most important ones. The second type is called collaborative product definition management systems (cPDm) where systems for management and collaboration around product data are central; these are typically PDM systems. The third type is applications for digital manufacturing. In this presentation the focus is on cPDm systems, and particularly PDM, RM, and SCM systems used in mechanical and software development. In this thesis the term cPDm is treated similarly as PDM.

3.5.1 Product Data Management Systems

In any project it is important to document, so as to ensure that everybody is on track with the project's vision. In a product development project, data about the product need to be stored and kept available for the development team. The system responsible for managing product-related data is called the Product Data Management (PDM) system. There are five basic functionalities in a PDM system (CIMdata 2002):

- **Information warehouse/vault:** The place where product data are securely stored
- **Document management:** To manage and use documents in an orderly manner. This includes document control capabilities, such as check-in/check-out.
- **Product structure management:** The arrangement of product definition information as created and changed during the product's lifecycle. It facilitates the management of product configurations and the Bill of Materials (BOM).
- **Workflow management:** The set-up of rules and procedures for work on the product definition and associated documents, managing engineering changes and revisions.
- **Classification management:** Allows similar or standard parts, processes, and other design information to be grouped by common attributes and retrieved for reuse.

PDM systems traditionally have focused on hardware (mechanics, electronics). Their extension and usefulness for configuration management of mechatronic systems (functions, software and hardware), including interfacing to domain-specific tools such as Matlab/Simulink and software development environments, have been shown to be feasible given that the tools have open APIs and provide means to customise the information models (El-Khoury 2006). Dassault has solutions that integrate well with discipline-specific tools in the mechatronic discipline (CIMdata 2005). Siemens PLM, for its part, claims to have good integration towards Rhapsody (CIMdata 2006). The support for mechatronics has only recently started to come into focus in PDM systems. It has, however, been possible to customise the PDM systems to manage software components just as with mechanical components in the past. This has not, however, been implemented in most companies since the general support for the software engineering process is low. Compiled software files have been imported into the PDM systems, but not the complete file structures and breakdowns. PDM systems have recently incorporated geometry-based mechatronic components such as wires and black boxes – e.g. Teamcenter Mechatronics, which is an extension of Teamcenter Engineering.

Figure 21 shows Boston Consulting Groups' view on the 2006 scope of PDM and extensions, incorporating the major vendors of PDM systems, including Dassault (SmarTeam, Enovia LCA and Enovia eMatrix), PTC (Windchill), and Siemens PLM (Teamcenter Engineering and Enterprise). For small enterprises, Autodesk has solutions that fit the needs at lower costs. SAP is a relatively new actor on the PLM/PDM market, and cannot offer a complete solution involving CAD and digital manufacturing as do the three major competitors. The comparison does not include any reference to tools used in the mechatronic discipline, which also can be connected to Figure 22.

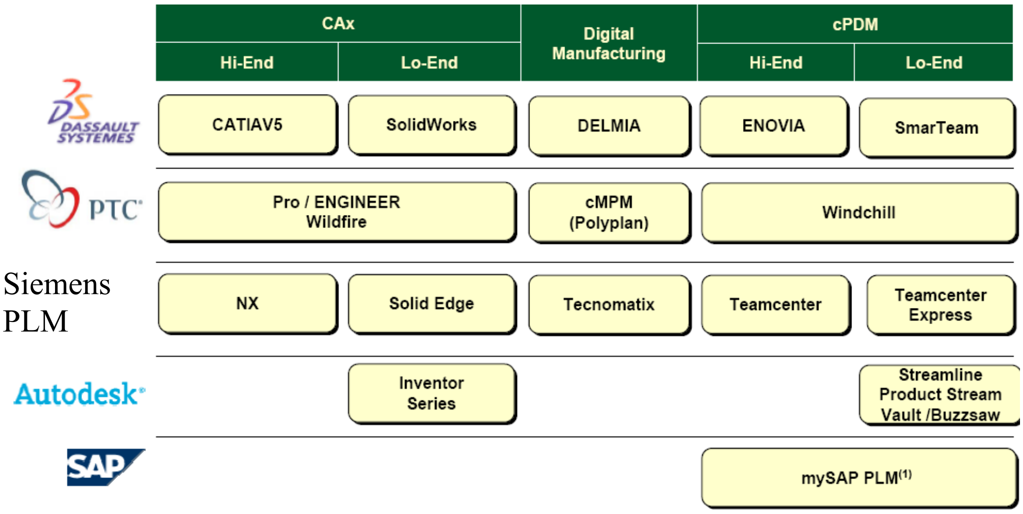


Figure 21. The product portfolio of actors (Boston Consulting Group, 2006)

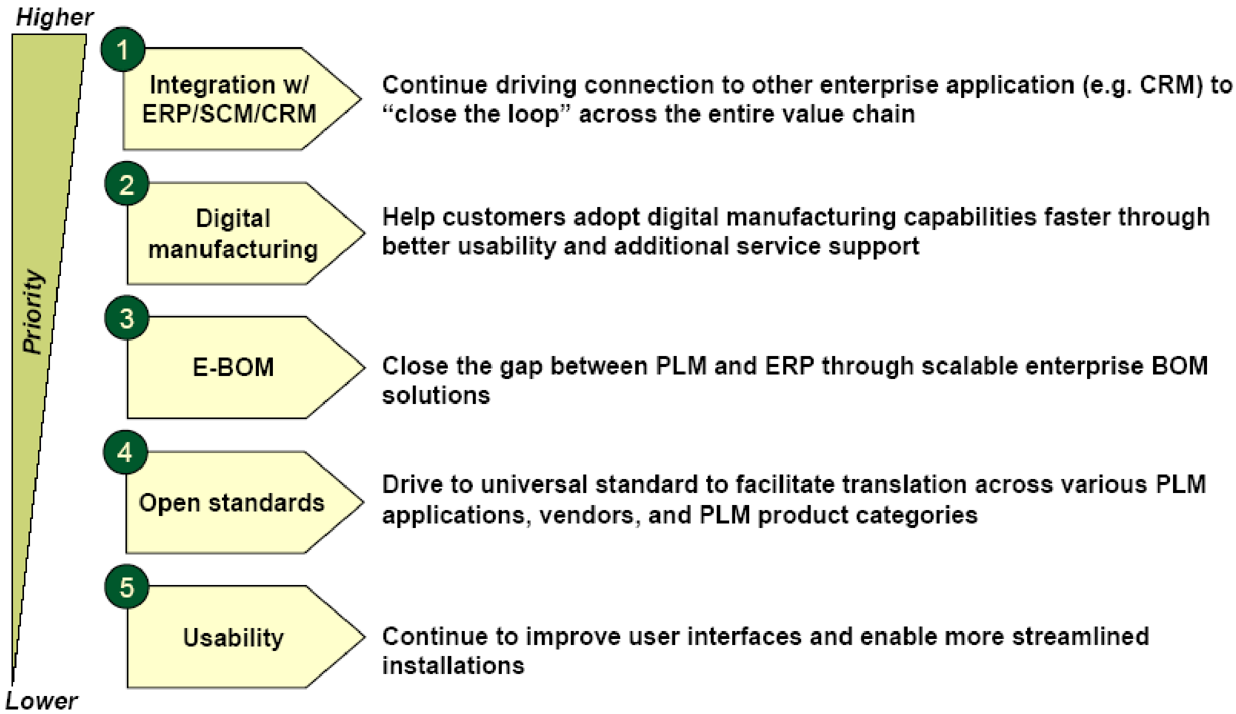


Figure 22. Priorities in PLM development (Boston Consulting Group, 2006)
(SCM stands for Supply Chain Management, CRM for Customer Relationship Management, E-BOM for Enterprise BOM, i.e. an integrated enterprise common BOM)

3.5.2 Software Configuration Management Systems

Software configuration management systems (SCM) is a means to manage software in a software development project. Research in SCM is based on four issues (Estublier et al. 2005):

- **Versioning**, to issue an identifier to objects that change throughout the development.
- **System Models and Selection**, support for modelling entire software systems, and to obtain (optimal) access to objects.
- **Workspace control**, the user interface where files are checked out and manipulated.
- **Building**, a function to build (compile) source code to executable files.

The main feature of SCM systems and what is different from a PDM system is the ability to concurrently edit several versions of the same file. This is a useful feature when working in large projects on the same software file. Other similarities and differences between SCM and PDM systems are shown in Table 2. The table is, however, a bit outdated since PDM systems today often include functionality for Configuration management, as shown in Paper B.

The future of SCM research is challenging two fundamental limitations of SCM: the focus on managing the implementation of software only, and the basic philosophy of SCM being independent of program language and application (Estublier et al. 2002). The first assumption calls for integration and management of other than software data, such as product data and requirements.

Table 2 Differences between PDM and SCM (Crnkovic et al. 2003)

Type of Functionality	PDM	SCM
Version management	Yes	Yes, with branch merge
Product structure management	Yes	No
Build management	No	Yes
Change management	Yes	Yes, well integrated with other processes
Release management	Yes	Yes, but weak
Workflow and process management	Yes	Yes, but weak
Document management	Yes	Partly
Concurrent development	No	Yes
Configuration/selection management	No	Yes
Workspace management	No	Yes
Roles	Yes	Yes, but weak

3.5.3 Requirement Management / Systems Engineering Tools

Requirement management (RM) tools or, in a wider sense, systems engineering (SE) tools are systems for management of requirements, solutions, and tests in the product development process. Many software bundles on the market use a PDM system for management of the technical solutions, but there is also basic functionality for managing technical solutions in SE tools, e.g. Teamcenter Systems Engineering (TsE). In general, SE tools are focused on requirements, and are often independent of e.g. CAD systems. PDM systems often offer functionality for requirements management (Malmqvist 2001). Recently integration efforts with mechatronic development have been made towards systems engineering tools rather than PDM systems, e.g. Rhapsody integration in TsE (CIMdata 2006b).

3.5.4 Product Lifecycle Management Systems

PLM is a broader concept than PDM, which takes in the whole lifecycle as well as the tools used for authoring data (Figure 23). PDM remains the foundation of a PLM system, but the term PLM is used to consider the product lifecycle and collaboration aspects regarding product data (CIMdata 2002).

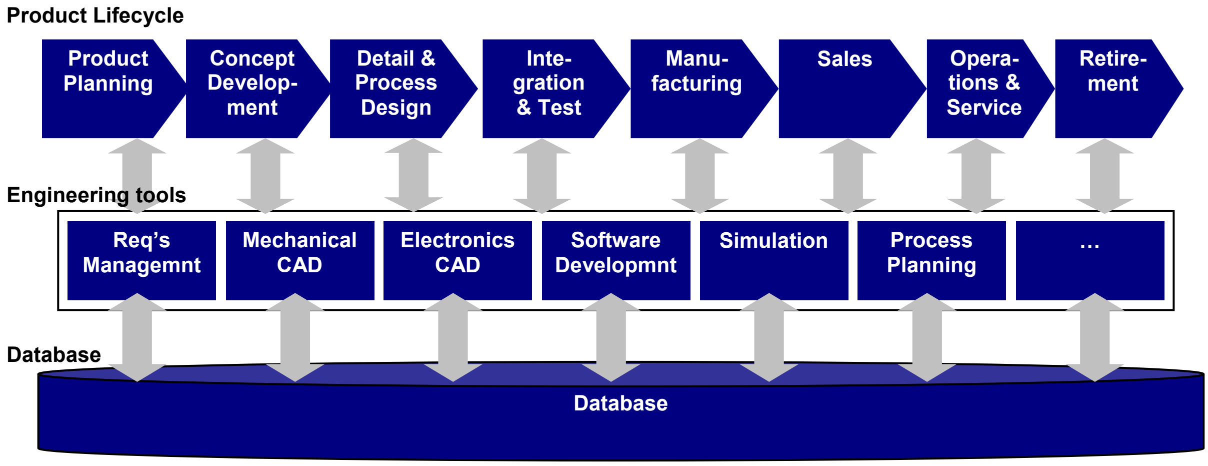


Figure 23. Product Lifecycle Management (Malmqvist 2005)

There are several somewhat different definitions of PLM and what is included, ranging from everything that is managed in a company to the product data used in the product development. In research, PLM is often referred to as a concept rather than a software bundle that could be bought on the market. This does not, however, prevent vendors of systems from calling their systems PLM systems, even though these systems clearly do not satisfy the definition of PLM in the Introduction chapter. The definition in that chapter can be compared with similar definitions below. The management of product data throughout the company and lifecycle of the product can be seen as a common denominator of these three definitions.

PLM is "A strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems and information." (CIMdata 2002)

PLM is the activity of managing a company's products all the way across their life-cycles in the most effective way. In doing so, it enables the company to take control of its products. (Stark 2005)

PLM is an information driven approach to all aspects of a product's life – from its design through manufacture, deployment and maintenance, culmination in its removal from service and final disposal – enabled by a set of highly integrated processes, methods and tools. (Ford Motor Company as cited by Turesson 2006)

Figure 24 shows the direct and indirect revenues of the market leaders of PLM according to (CIMdata 2008). A large proportion of the revenues are mapped towards PLM tools, but the proportion of the cPDm systems is growing more than the revenue from tools.

3.5.5 Areas for Future Research

Table 2 has been shown to be out of date, as PDM functionality has expanded to incorporate configuration and selection management.

On an engineering level, the PDM and SCM systems show differences due to differences in the development processes. For instance, PDM systems are still strong on product structure management, whereas this support is weak in SCM systems (Svensson and Crnkovic 2002).

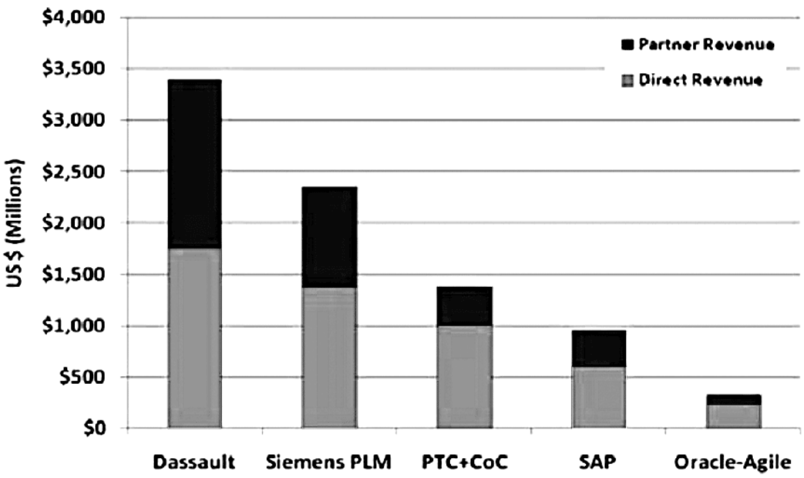


Figure 24. PLM leaders and their direct and indirect revenues in 2007 (CIMdata 2008)

The current trend in PLM research is moving towards more integrated solutions. The integration of mechatronic development is one of the major areas marketed to customers as shown in Figure 23. This can probably be connected with the fact that PLM suppliers have problems integrating mechatronic support in the PLM systems. That the PLM suppliers have had a mechanical focus in the past, while SCM systems have been developed separately, has led to a gap that is difficult to bridge.

Differences in processes are possible to resolve by e.g. a systems engineering approach, but software development supported by PLM systems has not yet been shown to work, as presented in e.g. Paper B. One of the identified problem areas is the lack of support for software components and management of software components on a level offered by SCM systems, in combination with the support of BOM and configuration management offered by PDM systems. Differences on a user level are particularly difficult to close, since e.g. version managements in the software discipline and the mechanical discipline are not compatible.

3.6 PLM Architecture and Integration

Integration of the disciplines does not only concern the systems used. Also collaboration and communication skills are specifically important in the multidisciplinary field of mechatronic engineering (Adamsson 2005). Integration aspects have been the focus of several researchers (Svensson and Malmqvist 2001; Hallin et al. 2004; Burr et al. 2005). Challenges when integrating systems involve defining the master source of the information, the level of integration required, and how processes should be managed that span over the two integrated domains. Integration depends also heavily on the legacy of information and the traditions of the company (CIMdata 2006b). There are primarily two approaches to integrating system and information levels. One is system level integration, where systems communicate with each other through common interfaces and export/import functionalities. The second approach is information level integration where the systems are integrated on a data level, with a common information model (Hallin et al. 2004).

Crnkovic et al. (2003) describe the problems of PDM and SCM integration. Several cases are described, as well as scenarios and approaches for successful integration. The need for information management and structured collaboration is essential in the industry today, since there are many people involved in the product development. The main cause of the challenges of integration PDM and SCM system is the fundamental difference regarding the visions, assumptions and underlying technologies in the two separate domains. Persson-Dahlqvist

(2005) conclude that there are three major factors which have to be considered during a successful integration: tools and technologies, processes, and culture and people's behaviour. Terminology and culture are factors to highlight.

Integration between systems has its roots in enabling information to be available to all parties that show a need. Traditionally this integration was built up over time by creating an interface between two separated IT systems one at a time. Svensson (2003) points out that the legacy PLM environment tends to be made up of a variety of applications and databases which were implemented every time a business need was recognized. This way of expanding the PLM environment also meant that much of the information was duplicated, and that a lot of time is lost in feeding the same information into different systems. As the legacy PLM environment usually has a common name, it is natural to think of it as being a system which can be replaced with another system fulfilling the legacy's functions. Burr et al. (2005) show that the integration in the PLM environment is not working properly, resulting in data losses, especially when handovers occur in the development process. Integration between systems can take place in different levels. Burr et al. (2005) suggest a Best-in-class integration, where the best software from each discipline is bound together on a higher level. They also suggest another approach called the All-in-one integration concept, where the master system is directly connected to the applications. The All-in-one integration concept is similar to an integration based on a PDM system, but extended with model-based development in order to better comply with the requirements of mechatronic development (El-Khoury et al. 2005). The approach is based on one single database where terminology and information are standardised and used in order to tie engineering applications together. Further, a PDM-centred integration of PDM and SCM is proposed by Do and Chae (2008), the main reasons being that PDM has a richer set of product evolution management functions than SCM and that it has a longer application history and incorporates product development standards. These approaches are further elaborated and evaluated in Table 3 in Paper C.

Service-oriented architecture (SOA) is an approach to designing software applications and, within the scope of this paper, a PLM system that is not dependent on a rigid server and client architecture of a multi-tier environment. SOA will make it possible to integrate systems that are heterogeneous (that have custom information models and processes), and is therefore a possible approach to bridging gaps between e.g. PDM and SCM systems under the PLM umbrella. A similar approach has been shown by Abramovici and Bellalouna (2008). The idea is to create services that collect, distribute and even modify information in several databases. These services are then reachable from e.g. the user PLM interface when a function that involves several disciplines has to be carried out. SOA is an architecture that can be enabled by a web-driven architecture by the use of java services that utilize communication protocols and standards such as XML, SOAP and WSDL for communication between independent tiers (Georgiev et al. 2007).

SOA as an industrial application has been evaluated by Lee et al. (2007). In their view, four aspects are important regarding a SOA: the services, the Enterprise Service Bus, Business Process Management, and Enterprise Portal. The services are defined as providers of reusable business functions in an implementation-independent function that is loosely coupled to other business functions. The service bus is the integration middleware where applications are connected by services. Business process management's main function is to provide integration of scattered systems, where SOA would offer a smooth integration. Finally, the enterprise portal is used as the presentation layer where users can take in the information provided by the service-oriented PLM system. SOA hybrids are possible where the SOA can be introduced stepwise, thus leaving room for the IT legacy applications to be phased out calmly, and other software to be used as interfaces towards the engineers. These composite applications are based on proprietary applications and interfaces and then enriched by the addition of open SOA interfaces (Gulledge et al. 2008).

In order to standardize the application of web services specifically for PLM systems, OMG and Oasis have developed their own set of standards independently. The OMG standard is based on ISO 10303 AP 214 and is recognized under the name PLM Services (Feltes and Lämmer accessed on 24/11/2007), where version 2.0 is the latest edition, still under revision as this paper is written. The second standard, Oasis PLCS PLM web services definition, is based on AP 239 (Vec-Hub accessed on 24/11/2007). The standard is further described in Srinivasan et al. (2008). PLM Services 2.0 is provided by the standardization body Object Management Group (OMG) (OMG 2006a) and has been developed together with representatives from the German automotive industry. It provides the developer with a set of rules and guidelines, a contract, according to which PLM-information is communicated, ordered and delivered. The PLM Services 2.0 specialty is that its starting points are the common workflows encountered in the PLM area, which should not be confused with processes and workflows embedded in commercial PLM software suites. The workflows are described on a more generic level, which means there is flexibility for company-specific processes, applications and information. An overall architecture of a PLM services implementation is illustrated in Figure 25.

3.6.1 Areas for Future Research

It seems that integration of product development systems has been directed for a long time towards finding a master system in order to manage all the data produced in a manufacturing firm. The approaches presented in research are not satisfying, especially with regard to the mechatronic discipline. Attempts in research have focused on integration of SCM and PDM systems, and have found working solutions (Crnkovic et al. 2003); but on a bigger scale involving more disciplines and the lifecycle, this has not been done and needs to be further investigated.

The information models (Chapter 3.3.1) all tend to be based on full-integration concepts. With recent efforts to develop looser integration concepts, the pros and cons have to be evaluated individually and against each other from the engineering, business and technical points of view. There are also emerging new technologies to share information in a way that simulates a single storage. SOA is one of these technology meta-repositories; Ball et al. (2008) is another.

The applicability of a SOA is believed to offer a looser type of integration making it possible to e.g. keep specific versioning (in the software discipline), and only the actually released versions (not the versions concurrent in work) are shared on an enterprise level. It is both an academic and an industrial challenge to make a flexible integration that works, while being able to manage introductions of new systems and phasing out old systems. It is also important that the integrations and architectures that are designed today do not become the legacy of tomorrow.

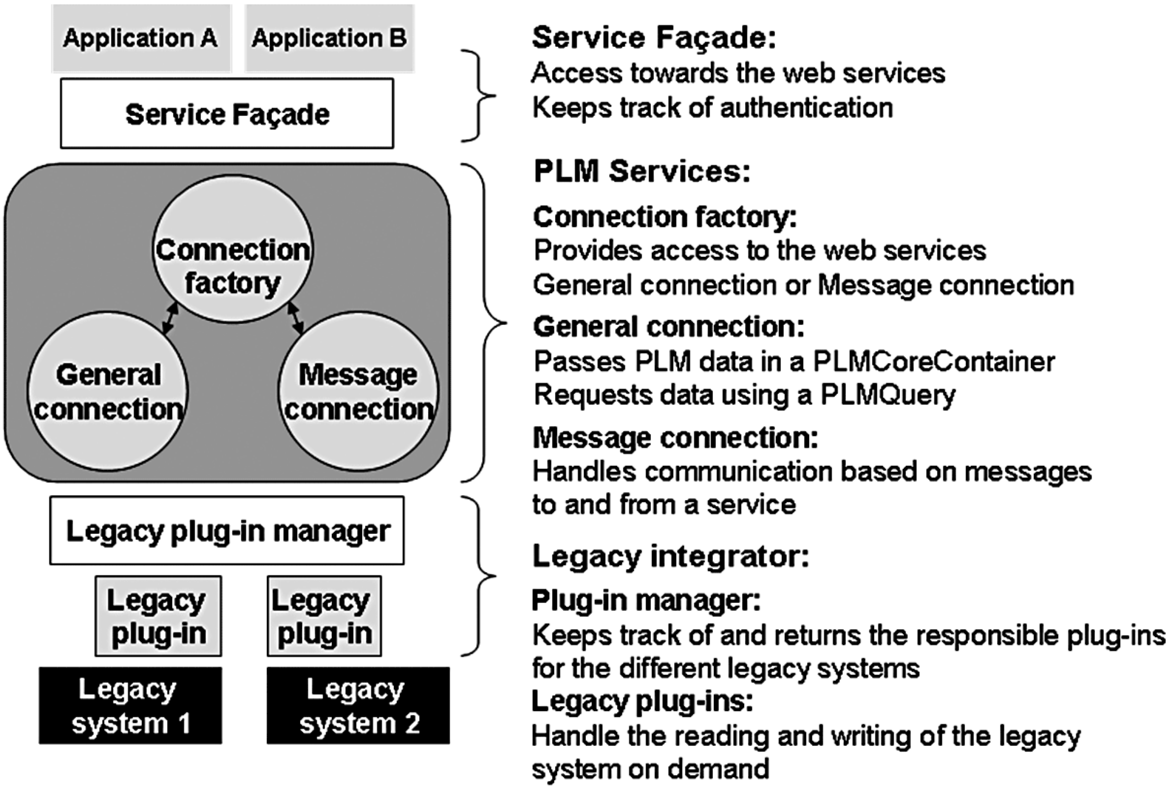


Figure 25. PLM Services (Ćatić and Andersson 2008)

3.7 Organisational Change

Since PLM and engineering information management are very large and complex organisational systems, planning for change in these systems is essential. It is not just about introducing new systems and thus adding to the pallet of IT systems used within a company; it is also about planning for the future, allowing the technology of the future to be integrated and to plan for continuous improvements. In the overall enterprise it is difficult to plan for the future and possible technologies that we today have no perception of. Instead, "the enterprise architecture must rather provide for the capability to enable change to occur rapidly, without undue resource utilisation, yet in a controlled manner and with minimal adverse impact" (Schekkerman 2003). Further, it is not the adoption of a new technology in itself that makes a strong strategy for survival of a business; it is rather the mindset of adaptability that is essential (Schekkerman 2003). A general process for how to perform major changes in a company is presented by Kotter, in Figure 26. The process contains eight main steps with specific tasks to perform during each step. The first four stages of the process are meant to prepare the organisation for the upcoming change, steps five to seven are the actual change, and the last step is an approach to make the changes stick and become routine within the company (Kotter 1996).

PDM implementation projects are more complex than ordinary IT projects (compared to organisational change management), and require re-engineering of the product development process to fit both the users' needs and the PDM system chosen (Sellgren and Hakelius 1996). One main difference with PDM projects, in comparison with other IT projects, is that PDM projects are unique and require customisations to fit the company (Pikosz et al. 1997). If the project does not have a realistic scope or understanding of the complexity of PDM, it is likely to fail. With this view, the introduction of a PLM system would require even more, since the scope in PLM is even larger. A systematic, primarily top-down approach in order to adapt to business processes and information modelling is suggested (Hallin et al. 2004). Regarding a large PDM/PLM introduction project in practice, Zimmerman et al. (2008) conclude with three main recommendations:

- Control and coordination between companies' different business units are extremely important in order to find the synergies across the lifecycle and across departments.
- It is important to break down the initial vision into subprojects with clearly defined activities and delimitations.
- A distinct and coherent PLM architecture that allows flexibility. The architecture needs to be defined and be consistent for every business layer.

A company's ability to adopt new IT systems, processes etc., is known as the adoption process. Rangan et al. (2005) state that "PLM deployments must establish business process principles which balance business process flexibility with system automation and ease of use and adoption". This is similar to adaptation theory, which considers the willingness to adapt to new technology, discussed by Rogers (2003). Organizational adoption of IS/IT solutions is mainly focused on two effect goals, namely product differentiation and lower cost (Spanos et al. 2002). In this case, the effect of the PLM systems contribution to these effect goals should be possible to evaluate.

Research in Product Lifecycle Management systems focuses on introduction aspects (e.g. (Garetti and Terzi 2005; Batenburg et al. 2006). In order for a future PLM system to be successful, it is important that it is introduced and packaged in such a way that it is appreciated by its future users, the designers. Since PLM systems are a relatively new concept, the research targeting PLM for mechatronics specifically is sparse, but Garetti and Terzi (2005) point out that organisational change management theories are relevant and applicable to PLM systems introduction.

A company's ability to adopt new IS/IT solutions has been found to be different between different business sectors (Bayo-Moriones and Lera-Lopez 2007). This shows that companies have different prerequisites depending on culture and background. One important first step is to estimate the PLM maturity of the organisation (Batenburg et al. 2006). In mechatronic engineering and in the automotive industry, this PLM maturity could be regarded as high, since the complexity of solutions and requirement already has made it necessary to categorise different levels of abstraction regarding product and requirements. Turesson (2006) states that automotive companies typically have a PLM legacy that has evolved as long as computers have been present in product development, i.e. during the last 30 years. The second step for a successful PLM introduction would be to define and map the information and to gain an understanding of how engineers work (Lowe et al. 2004; Ottersten and Balic 2004). These would incorporate mapping legacy systems, information models, and processes that would call for a bottom-up approach (Hallin et al. 2004).

(Garetti and Terzi 2005) suggest that there are two main ways to introduce a PLM system in an organisation: either an overall step-by-step procedure, or by niche and follow-up projects. When considering a niche project and follow-up approach (which is close to a bottom-up approach), a quick implementation among highly motivated people is done; however, validity of the niche project as a trustable pilot scalable to the whole company is a problem. The step-by-step approach seems to be more reliable regarding collection of user requirements, but requires a lot of time for analysing the company needs.

1 ESTABLISHING A SENSE OF URGENCY
- Examining the market and competitive realities
- Identifying and discussing crises, potential crises, or major opportunities

↓

2 CREATING THE GUIDING COALITION
- Putting together a group with enough power to lead the change
- Getting the group to work together like a team

↓

3 DEVELOPING A VISION AND STRATEGY
- Creating a vision to help direct the change effort
- Developing strategies for achieving that vision

↓

4 COMMUNICATING THE CHANGE VISION
- Using every vehicle possible to constantly communicate the new vision and strategies
- Having the guiding coalition role model the behavior expected of employees

↓

5 EMPOWERING BROAD-BASED ACTION
- Getting rid of obstacles
- Changing systems or structures that undermine the change vision
- Encouraging risk taking and nontraditional ideas, activities, and actions

↓

6 GENERATING SHORT-TERM WINS
- Planning for visible improvements in performance, or "wins"
- Creating those wins
- Visibly recognizing and rewarding people who made the wins possible

↓

7 CONSOLIDATING GAINS AND PRODUCING MORE CHANGE
- Using increased credibility to change all systems, structures, and policies that don't fit together and don't fit the transformation vision
- Hiring, promoting, and developing people who can implement the change vision
- Reinvigorating the process with new projects, themes, and change agents

↓

8 ANCHORING NEW APPROACHES IN THE CULTURE
- Creating better performance through customer- and productivity-oriented behavior, more and better leadership, and more effective management
- Articulating the connections between new behaviors and organizational success
- Developing means to ensure leadership development and succession

Figure 26. Main steps in organisational change management (Kotter 1996).

Difficulties with successful IT tool support lie in education and commitment (Sutinen et al. 2004). Sutinen et al. also suggest several guidelines that are important when addressing the usability of IT tools. For example, it is important that the people in charge of the implementation have sufficient knowledge in the craftsmanship, in this case good knowledge in systems engineering. In order for a tool to become easily accepted by users, it must fit into a company's existing development process and be easily integrated with tools that are already in use (Beskow 2000). In addition, presumptive users have to experience a need for an IT tool or system, in order to become motivated users (Lindahl 2005). Proof of a successful PLM implementation is difficult to ensure, since the true benefits reside within the organisational activities (Dhillon 2005). With this focus, more effort should be devoted to the design engineers, since they are the actual users of the systems and their satisfaction is of main importance to success and progress.

It has been shown that close collaboration between IS supplier and user when developing and introducing IS enhances satisfaction and motivation among users (Malvius et al. 2006). Introducing the user early in the introduction process, and adopting the process after groups of users with similar needs, also enhance the motivation (Bergsjö and Malvius 2006). There are several approaches in how to introduce information management systems (Garetti and Terzi 2005; Lindahl 2005). Turesson (2006)states that automotive companies typically have a PLM legacy that has evolved as long as computers have been present in product development. When introducing IS, it is important to define and map the information and to gain understanding of how engineers work (Lowe et al. 2004; Ottersten and Balic 2004).

Information technology is seen as an important focus area when discussing performance in product development (Leenders and Wierenga 2002; Haque and Moore 2004). The efficiency regarding IS/IT shows a great improvement potential. Management initiatives and benefits with better IS/IT do not correlate with the needs and benefits experienced by the IS/IT users (Malvius et al. 2007a). This has the impact that management purchases large corporate IS/IT without having correct user requirements on the solutions, and thereby relies too much on the prerequisites and requirement communicated by the IS/IT suppliers.

There is no commonly accepted way in industry to measure performance of information management (Malvius et al. 2008). IS are dependent on a number of organizational and technical variables that affect the successful outcome of IS introductions and that need to be accounted for when evaluating the impact IS have on, for example, efficiency and quality. This circumstance adds to the problems with measuring IS impact on product development. Several evaluation methods in combination with corporate strategies and IS/IT are needed in order to be successful in product development (e.g. Vielhaber et al. 2006). There exist a number of methodologies for evaluating the success of an IT project, but they are dependent on company experts' opinions and are therefore highly subjective in nature (Rodriguez-Repiso et al. 2007). One feasible way is to measure collaboration and interaction effects on product development (Kahn 2001); another is to measure process introductions through implementation success values (Börjesson and Mathiassen 2004; Knippel and Schulz 2006). There are also more direct behavioural ways to measure user satisfaction of IS (Lee et al. 2006b). But in order to obtain improvements with IS, IS need to work in synergy with other relevant variables in an organization (Abrahamsson 2004).

3.7.1 Areas for Future Research

Although the user is said to be the focus of most introductions, it is important to gain further knowledge about engineers' attitudes towards the use of information management systems in product development. There are studies that focus on the user perspective (e.g. (Lowe 2002), but there remain issues of information exchange and collaboration in complex product development and the difficulties with tool and system integration, including diverse traditions within multidisciplinary contexts that have to be further researched. The cookbook-related introduction processes used in IT introduction projects might not be applicable to such large-scale introductions as the introduction of a company-wide PLM system; this has also been shown by Zimmerman et al. (2008). The field of organisational change management can contribute methods and mindsets when it comes to implementing PLM, since the projects are so large and span so many organisational units that political rather than technical decisions need to be taken. It is believed that by structuring and comparing the organisation's interested parties into groups and assessing their individual needs, a better understanding of the needs and challenges for PLM introduction and customisation can be achieved.

3.8 Identified Gaps in Research

There are unique problems with mechatronic design and the ability of IT tools and systems to support the specific needs. The increased amount of information available, and the need to manage this information from several and traditionally different engineering fields, have made it evident that it is no longer possible to design without solid knowledge about what is going on in related fields. With a different set of development tools, vocabulary and process traditions, the mechatronic field now has to confront the design tasks as an integrated design team. PLM systems and their PDM predecessors show promising signs of being able to support this. However, it is not (only) a matter of collecting and presenting information for designers. There must be found suitable means to categorise and identify the information that is needed. Not only CAD drawings, but also requirements, systems and functionalities, have to be managed and on different levels of detail. Performing these changes is not an easy task, and the end-user, that is, the designer, may or may not understand the underlying reasons for implementing PLM systems. It is important that designers can be motivated by the PLM approach, which makes it possible to increase efficiency by e.g. reducing the current information-management complexity of, for example, different application and system interfaces that confront the designer in the mechatronic field.

The gaps in research that are essential to investigate further, in the field of PLM, have been identified as follows:

- Successful integration of mechatronic product data in PLM systems has not been shown. This will be a focus in Papers A, C and D.
- Functionality for variant management and configuration management where software is regarded as components has not been shown. This is presented in Papers A and C.
- The user benefits of an integrated approach to mechatronic data have not been fully tested and evaluated. This discussion is started in Paper B, and continues with a higher user and management focus in Papers E and F.
- The current state of art and possibilities with integration are continuously changing. The possibilities of commercial systems to manage mechatronic product data have to be investigated, to monitor whether foundations of previous research have changed. This is mainly done in Papers A and D.
- Integration architectures focusing on the requirements on an enterprise level for information management systems remain an open-ended question in related research, with no definite answer. These questions are further elaborated in Papers A, C and D.
- The ability to manage large organisational change projects, such as a PLM introduction product, and the user aspects of a PLM introduction are limited in current

research. Methods to prepare a PLM introduction as well as improving the current PLM situation are presented in Papers F, G and H.

This research must focus on the basis of these gaps in order to investigate how integration of mechatronic development can be implemented and integrated in PLM systems. Further, it has to be investigated how this will affect and interact with the business needs.

4 RESULTS

In this chapter the appended papers and the main conclusions drawn from those studies are presented.

4.1 Paper A: Implementing Support for Management of Mechatronic Product Data in PLM Systems – Two Case Studies

4.1.1 Purpose

The purpose of this paper was to demonstrate the possibilities of implementing support for mechatronic engineering in a commercial PLM system. Specifically of interest was to investigate the possibilities of managing software requirements and code within a PLM system. This study was performed in collaboration with two companies that both develop mechatronic products: a manufacturer of passenger cars and a manufacturer of electronic test equipment. The study was performed in order to investigate to what extent currently available PLM systems can manage mechatronic product development.

4.1.2 Results

The research was aimed at designing demonstrators able to manage product data from several disciplines in mechatronics, that is, software, electrical and electronics, as well as the mechanical product data. In order to show the applicability of systems adapted for both large and small companies, two separate PDM/PLM systems were used that corresponded to the needs of both larger and smaller firms ("advanced" and "basic" systems). The information model (Figure 27) was derived from related research (Collier 1999; Andersson et al. 2002) and took in the mechatronic development aspects.

The two systems were tested to incorporate a variety of interdisciplinary information. Management functionality such as version management, configuration management, engineering change management, and process management was tested in the study. Differences in PDM/PLM functionality differ between the tested systems; e.g. the basic system did not (in the version used) have any capabilities to manage configurations. The advanced system was better suited for handling complex relations, since there are a variety of connections that can be identified as connecting components together. The basic system does, however, fulfil the basic functionality needed by the smaller company at a lower cost.

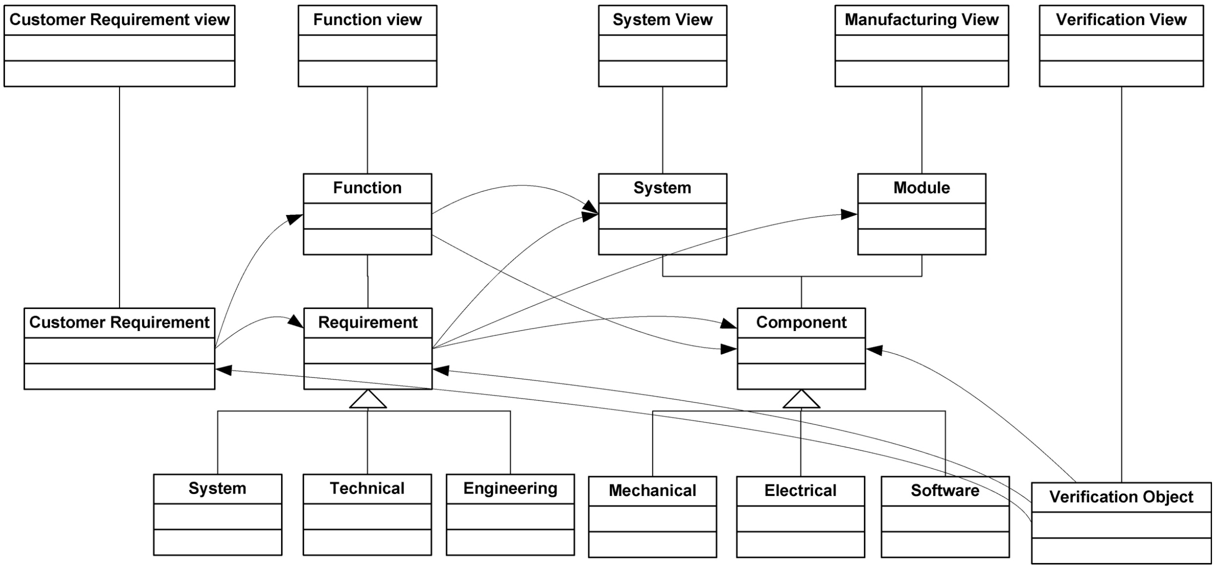


Figure 27. Information Model used in the demonstrators (Paper B)

4.1.3 Conclusions

The Paper concludes that it is feasible to create an integrated information model for mechatronic development and implement it in a PDM/PLM system. The differences, between large and small companies producing complex products, do not affect the principles of an integrated information model. The large company requires more formal procedures, which is somewhat reflected in its need for a more detailed information model, but the general principles regarding management of mechatronic data are common.

It was further shown that the PDM systems of today will not support the development of software without changes in the working procedures of software engineers, as PLM systems cannot manage software files and concurrent versions in the same way as SCM systems do. Since a large company mainly works with specifying software, and not so much with actual software development, it was concluded that changes in the development process were possible.

4.2 Paper B: Architectures for Mechatronic Product Data Integration in PLM Systems

4.2.1 Purpose

The purpose of this paper was to explore different types of architecture for connecting product information management systems used in mechatronic engineering, namely software configuration (SCM) and product data management (PDM) systems. Several approaches are possible and are discussed separately. Integration between systems does impact on the organisation function and how designers work.

4.2.2 Results

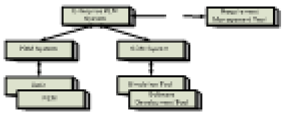
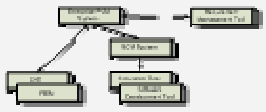
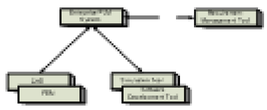
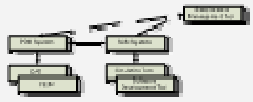
The paper analyses four major ways in how to integrate the systems, and which advantages and disadvantages these approaches have. These are presented as *Best-in-class*, *One-integrator*, *All-in-one*, and *Peer-to-peer*. Advantages and disadvantages of the different integration concepts are presented in Table 3.

4.2.3 Conclusions

This study concluded that there are advantages and disadvantages with all approaches of SCM and PDM integration. In the end, the choice of which approach to use boils down to the prerequisites and aims of the specific company. The amount of control, creativity in the processes, and tools and systems in the portfolio will considerably affect the choice of how to perform integration. Several conflicting requirements that need to be reflected upon were identified:

- To what extent the company wants to rely on a single PLM supplier. One single supplier will ensure smooth integration between systems and tools, but other suppliers might offer better solutions in a particular field, which then requires a compromise.
- A high degree of functionality in tools and system will make it possible to speed up development times for the individual engineer, but might make integration and data integrity more difficult since all designers cannot manage all functionality of the whole tool portfolio.
- Customisation or standardisation will affect the possibilities to perform upgrades of a system in the future. If a system is taken off the shelf it will be easy to perform upgrades, but with a customised system upgrades could require a lot of work in order to customise the new version.
- Adapting the system to the development process will take time and require customisations, but the transition towards a new system will probably be easier for the designers. Using an off-the-shelf product will almost always require the designers to change the way they work.

Table 3: Integration Approaches for Mechatronic PLM systems (Paper C)

Approach 1: Best-in-class	Approach 2 One-integrator	Approach 3 All-in-one integration	Approach 4 Peer-to-peer integration
			
Description One master system that allows subsystems (PDM and SCM)	**Description** One of the subsystems is also used as a master system.	**Description** There is only one master system. (Single source.)	**Description** There is no master system. Communication is performed directly between subsystems.
Advantages • Best tool for each discipline can be selected • Low introduction resistance • Can replace a subsystem without effect on other subsystems • Can work with standard protocols without involving the specific tools • Reduced risk of inaccurate communication between tools •	**Advantages** • High support for one of the disciplines • Quite high support for other disciplines as they can keep their existing subsystem • Can be based on PLM supplier bundles	**Advantages** • Only one central database is used • The tools can reach all data, since they do not require a subsystem to reach the database level • The correctness of the data is assured (only in one place) • Easy to uniformly manage changes and versions • Can be based on PLM supplier bundles	**Advantages** • Not dependent on a single software or database • Less server communication • Not dependent on a single supplier
Disadvantages • Two communication levels to manage • Loss of data between systems with separated databases • Data can be stored in several places • Complex management when the same data are represented in more than one database • Can lead to bugs since a system is added on top without revising the existing subsystems	**Disadvantages** • Requires additional customizations for one system to control the other, compared to using a complete bundle • Difficult to replace the tools directly connected to the integration level	**Disadvantages** • Needs heavy customisation or adaptation of tools and processes • Beneficial with tools that uses standard formats • High costs to replace systems and tools (supplier-dependent) • Updates and introduction of a new tool involve the top system	**Disadvantages** • Difficult to replace tools that are not standardised • Difficult to supervise and to control • Difficult to find and correct data errors • Restriction and rights are less manageable • The data are stored and managed by several tools and databases • All tools have to be customised in order to communicate with other tools
Summary Controllable integration where the most appropriate tool can be chosen for each discipline	**Summary** A compromise where tools and systems that are difficult to integrate can coexist	**Summary** A fully integrated system where data integrity is ensured	**Summary** A flexible solution where all tools co-exist with a robust but difficult to manage web of databases

4.3 Paper C: Product Lifecycle Management for Cross-X Engineering Design

4.3.1 Purpose

The purpose of this paper was to continue to evaluate possible architectures for PLM integration. While cross-x engineering features at least the three dimensions, the focus of this paper was the cross-discipline dimension (Figure 28). The objectives were to derive guidelines and principles for future solution concepts, and to present different options for such concepts based on two major cross-x PLM processes – namely, engineering change management (ECM) and configuration management CM. Whereas, historically, pure mechanical design occurred only in the bottom-left-back box, the challenge now is to manage the complete multidimensional landscape shown in Figure 28.

4.3.2 Results

The current landscape of integration is currently a landscape with many islands, where integration towards the main PDM system is difficult. This was a similar problem for both case companies. In order to perform functions such as ECM and configuration management in the mechatronic development, these islands have to be tied together.

The proposed architecture for performing this is a relatively loose integration concept similar to the Best-in-class approach in Paper B. The difference is that the use of an SOA makes it possible to manage the problem of redundant information (Figure 29).

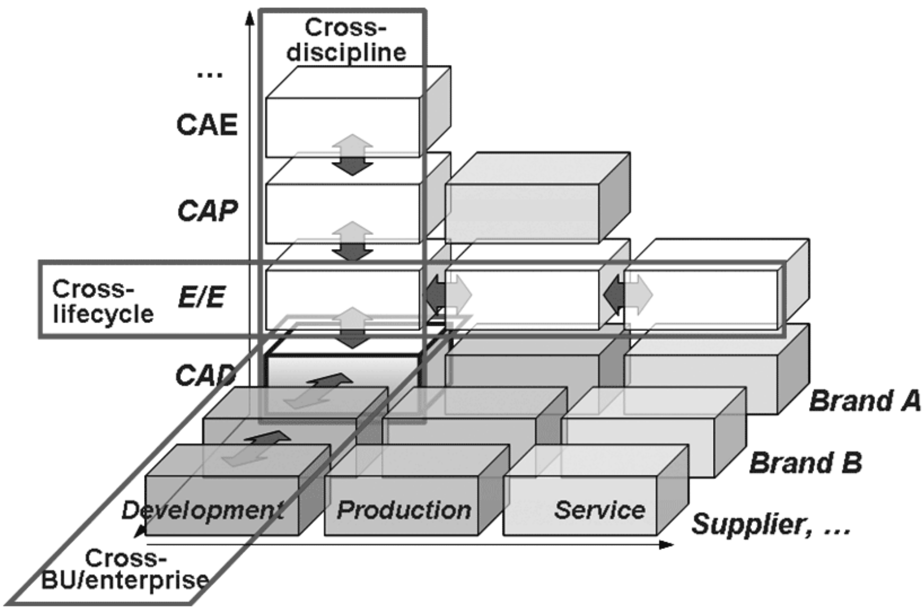


Figure 28. Cross-x engineering design dimensions. (Paper A)

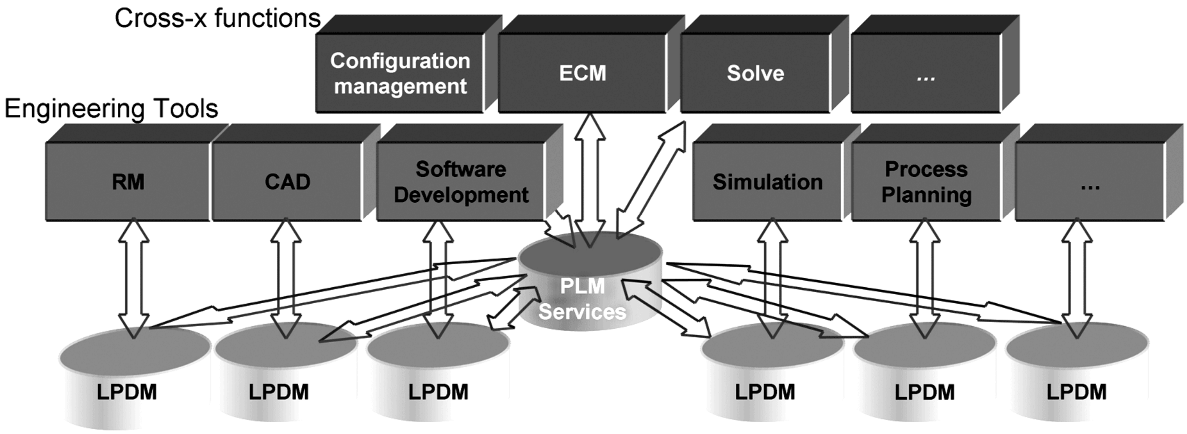


Figure 29. State of Art, a service-oriented approach with a uniform PLM interface towards the integration database. (Paper A)

4.3.3 Conclusions

The study concluded that PLM for cross-x engineering design is not yet a reality but the companies have strategies moving in that direction. In this progress towards obtaining a truly cross-x PLM system, five major points have to be considered: *Modularity*, *Central coordination*, *Standard communication*, *Minimum process redundancy, and General modelling constructs*.

- *Modularity:* Future PLM layouts will have to support distributed, fast-changing processes, applications, and local data storages. This can be achieved efficiently only by a modular approach replacing the monolithic legacy systems with highly independent, but strongly interlinked, domain-specific subsystems. Engineering applications have to be supported by domain-specific, application-near, local PDM databases (LPDM). There must be means to flexibly add or replace such components.
- *Central coordination:* In order to link the domain-specific modules together, a strong central coordination unit is required. On the IT side, this will have to be realised by some kind of integration layer. This layer will support the modules and their communication by central functions such as access management, and a minimal, potentially standardised, domain-spanning data object and product structuring model (Vielhaber et al. 2006). Besides the technical view, it is of utmost importance to manage this coordination also on a domain-spanning organisational level.
- *Standard communication:* In future PLM layouts, data flow will include all domains of the company. It will no longer be possible to manage a multitude of bilateral and proprietary interfaces. Instead, a strong standard for both communication and information structure is required in order to tie the systems together with loosely tied services SOA. This communication standard is preferably based on a standard data model such as ISO 10303.
- *Minimum process redundancy:* In a distributed modular PLM environment, methods and process step responsibilities should be clearly assigned, to avoid data redundancy. In a loose integration concept, strict rules have to be applied in order to avoid the same data being stored in different LPDMs. Cross-x PLM services will reduce the need for replication of functionality across different engineering tools.
- *General modelling constructs:* In order to keep track of the information within distributed databases' metadata to express conditions of use, cross-x would facilitate communication. Internally this added metadata would not affect the LPDM system but would be used to express cross-x relations and e.g. facilitate CM and ECM.

4.4 Paper D: Implementing a Service Oriented Architecture Focusing on Support for Engineering Change Management

4.4.1 Purpose

The purpose of this paper was to further evaluate architectural PLM issues by implementing a demonstrator for service-oriented architecture (SOA). In doing so, two test cases were implemented based on an industrial reference case as well as an academic hypothetical case, involving engineering change management including automated simulation and evaluation of the case. The main purpose was to provide the decision-makers with better change impact analyses, and the designers with a possibility to test several alternatives to a particular change.

4.4.2 Results

In order to support the engine development process, it was proposed for the first demonstrator to evaluate how a change in one part of an engine affects other parts. The initial idea was to use an analysis application along with a configuration application which provides a simulation analysis with correct inputs for the unchanged subsystems. Finally the analysis would be performed by simply comparing the new characteristics with corresponding requirements. The communication of data and execution of applications would be performed through a service-oriented PLM architecture based on PLM services 2.0, to ensure flexibility along with real-time access to the right data accounting for possible changes that might have occurred to other subsystems.

The approach proved hard to realize in its full scope, due to the simulation application being hard-coded with product parameters for only one engine configuration. This made the need for a configuring application obsolete. This meant that the simulation could only answer how changes in the turbo charger affected the rest of the engine. The utilization of a service-oriented PLM architecture was used to communicate data from different sources. When the analysis is done, unmet requirements and exceeded specifications are reported back to the initiator of the change.

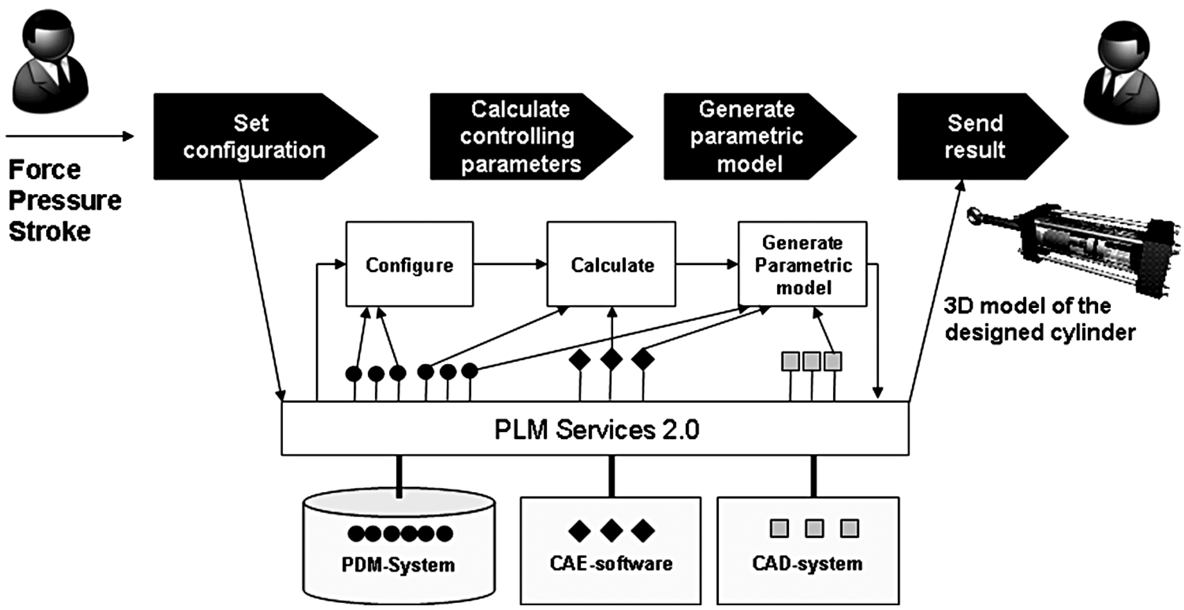


Figure 30. Hydraulic Cylinder process (Paper D)

The second demonstrator (Figure 30) aimed to show a more integrated way to work with analysis and evaluation software, based on a parametric CAD model of a hydraulic cylinder system. The connection to CAD and visual information about the EC is one step to further automate the EC process. Also software parameters to control the electronic system of the hydraulic cylinder are included in the EC in order to demonstrate the integration of several disciplines in product development. Compared to the turbo demonstrator, this is not based on a real industrial case, but it is intended to show possibilities of parametric design and analysis software that fully comply with the principles of integrated and parameterized product descriptions.

PLM architecture is improved since a SOA allows transparency and flexibility in IT integration, whereas supplier suites and single-source solutions actively work against this principle. In a SOA that is based on an open standard such as OMG PLM Services 2.0, the principles of a SOA of modularity, central coordination, standard communication, general modelling constructs, and minimum process redundancy can be managed.

The control of the company's business processes means that the company does not outsource the way it is doing business to an IT supplier, who does not necessarily understand the requirements in a particular business. The service-oriented PLM architecture allows for flexible integration of the current business processes and instead puts demands on IT suppliers to support standardized interfaces, rather than forcing every company to work according to their PDM system logic.

Superior usability is achieved since information services are created, focusing on a specific need of an engineer or a development process. These services do not change the way people used to work with the applications, but rather add a new service layer for those who benefit from it, and those are most likely engineers and managers working cross-functionally with new and innovative products. It is concluded that a service-oriented PLM architecture is an efficient IT architecture that enables multidisciplinary integration and collaboration. In this context it is also concluded to be the most promising architecture to support ECM.

4.4.3 Conclusions

In this paper it was concluded that a service-oriented architecture can benefit both user and business perspectives of PLM. These ways include, but are not limited to, issues regarding PLM architecture, control of the business logic and superior usability. The applicability has also been tested practically with the use case from change management in a turbocharged diesel engine and a fictitious example involving the engineering change and change impact analysis of a hydraulic cylinder. This demonstrator has been developed using OMG PLM services 2.0, which has been shown to be a suitable standardization effort. The framework has been shown to be applicable to support ECM along with two developed KBE applications that simulate effects of a change in real time, as the product is updated in the PLM system.

4.5 Paper E: Balancing Operational and Strategic Impacts on Information Management

4.5.1 Purpose

The purpose of this paper was to achieve better interdisciplinary and inter-lifecycle integration in information management in the SE process. Similarities and differences between designers and top and middle management regarding experienced needs, benefits and goals with information management are explored in this paper.

4.5.2 Results

It was found that management focuses on strategic needs in the organization, interdisciplinary development and the product development process, as well as platform reuse and efficiency when developing new products. The focus and commitment is on ensuring good product quality through formalized processes. When it comes to problems in information management, the main interest lies in IS, e.g. different commercial IS and IS suppliers and their advantages. Since top management is in charge of the budget, the focus is on time and cost. If organizational change improvements are difficult to measure, the funding of the projects are restrictive. The interviewed designers have gotten used to the current work conditions and accepted that information management is a problem that is easier to solve with e.g. a telephone call than a search in the IS. The designer needs regarding information management focus on support for individual work procedures, and improved disciplinary IS/IT functionality. The designer needs tend to be narrower than the managerial ones, especially since EE designers tend to handle a lot of product information, which means that access to reliable and updated information is important. Needs common to designers and managers are listed below:

Management needs:

- higher commonality
- standardized IT/IS environment
- shorter lead-times
- frontloading PD
- higher quality
- interdisciplinary work
- lower cost

Designer needs:

- domain-specific IT tools
- more core design work
- efficient information retrieval
- structured information
- data integrity
- earlier testing

The different viewpoints of management (including middle management) and designers are illustrated in Figure 31, along with the identified organisational gaps.

4.5.3 Conclusions

There exist several organisational gaps regarding the goals, needs and benefits of information management and IS/IT in a company. It is concluded that there are different drivers concerning information management at different organisational levels within the organisation. This is something that can be managed by identifying the drivers and mapping them towards each other. In many cases there exist no conflicts, but where they exist they are identified and can be managed. An approach to identify the different drivers is presented in Table 2.

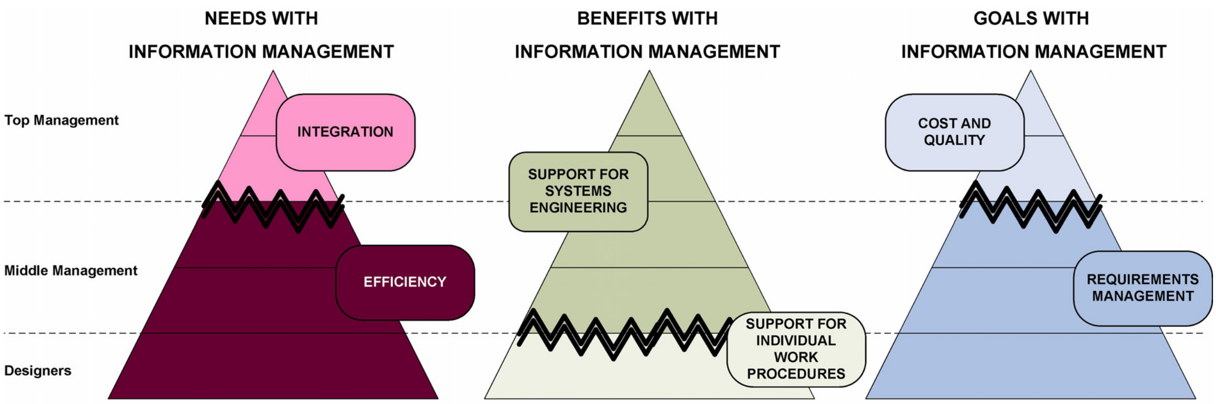


Figure 31. Identified gaps regarding needs, benefits and goals with information management. The zigzag patterns illustrate where the identified gaps are located.

Table 2. Designer needs stated in the matrix reflect efficiency needs in information management, while management needs relate to needs for integration in information management. Green boxes indicate non-conflicting needs and point out synergies between possible benefits with integration of information. Red boxes are seen as conflicting management and designer needs that are difficult to manage. (Columns 1-3) (Paper E).

designer needs / management needs	1 domain-specific IT tools	2 more core design work	3 efficient information retrieval
A higher commonality	Customized tools make transferability difficult	Reuse of existing solutions	Increased possibilities to better reuse information / know where to find it
B standardized IT/IS environment	Hard to tailor standardized IS to fit domain-specific IT tool	Could reduce time spend on information searching but might be more complicated to user	Information is standardized and easy to locate
C shorter lead-times	Tailor-made IT/IS that fit SE process reduces lead-time	Higher work pressure on a shorter time basis	Total lead time affected
D frontloading PD		Reduces late work, but initially more work is needed	
E lower cost	Domain-specific IT tools leads to higher maintenance costs	More personnel or longer development times	Initial investment costs vs. long term benefits
F inter-disciplinary work (SE)	Difficult to exchange information between disciplines		Enables information transparency and exchange
G higher quality	Domain-specific IT/IS to solve specific tasks	Enables more time for control of work and follow-up	Enables more time for control of work and follow-up

Table 2. (Continued, Column 4-5) (Paper E)

4 structured information	5 data Integrity	6 earlier testing
Increased possibilities to define information	Increased possibilities to identify and trace relationships	
Structure is easier to maintain with standardized IT/IS	Easier to trace and view info	
		Reduced time spent on testing vs. reduced total time for testing
		Errors are identified early
Enables information transparency and exchange	Ensures correctness of information	System view, verified systems
Enables more time for control of work and follow-up	Ensures correctness of information	Possible to identify risks in early SE stages

4.6 Paper F: Shifting Lead as PLM Introduction Strategy

4.6.1 Purpose

The purpose of this paper was to evaluate introduction strategies in order to gain maximum user acceptance for a global PLM system used in electrical and electronics development.

4.6.2 Results

It is not going to be economical to satisfy every user need within an entire organisation. Satisfying all needs would also be practically difficult and this hypothetical solution would most certainly contain overlaps that require extra development costs of the IS without gaining any major advantages. By balancing disciplinary needs this way, improved efficiency in the PLM system can be obtained. Allowing different stakeholders in different phases of the introduction of an IS/IT, Shifting Lead, enables scalable PLM support to a majority of users. The approach is further elaborated to incorporate system integration approaches towards the emerging enterprise PLM system. This approach is illustrated in Figure 32.

By identifying IS user needs, the interest group that experiences the most dominant need is allowed to set the IS framework. Responsibility can be distributed in the same way as technology development is distributed across brands to ensure specialization and high quality of technical solutions.

4.6.3 Conclusions

The question of how to obtain a PLM solution that satisfies IS user and business needs in a way that is technically possible is elaborated in this paper. By applying a Shifting Lead approach, in organisations developing complex products, the introduction of PLM is approached according to the needs from different engineering disciplines. It is argued that introduction groups should be chosen according to receptiveness to change and not primarily clustered according to development group, discipline or brand-belonging. The approach of Shifting Lead in introduction projects allows user groups and departments with dominant needs to take lead in the customization and introduction projects, i.e. to be the group that states the requirements on the IT/IS. The system solutions can then be adopted for other user groups, expecting reduced rather than increased need for IT/IS functionalities.

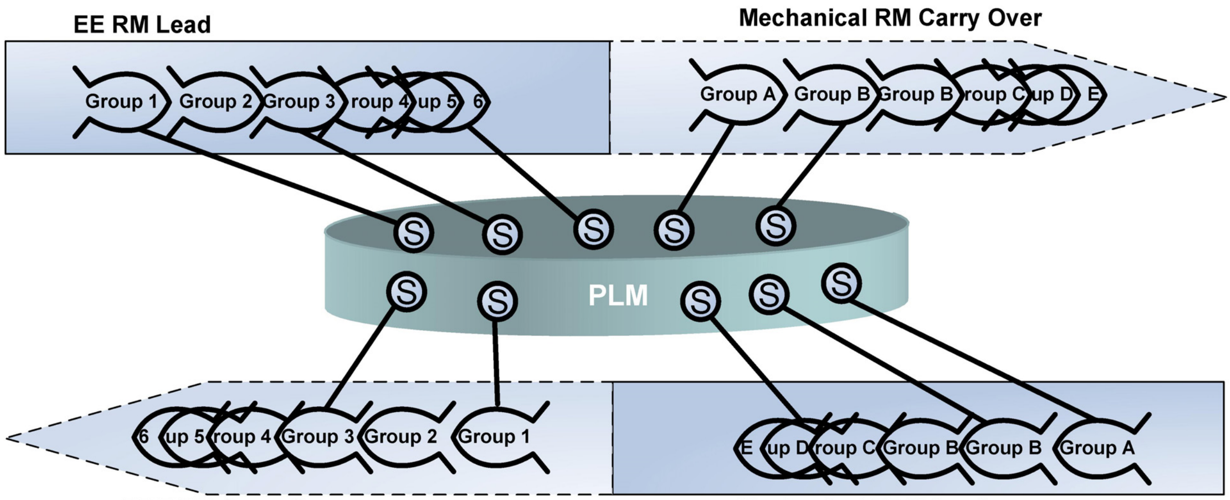


Figure 32. A step-by-step introduction process for the exemplified PLM project for addressing the needs in different engineering disciplines.

It is claimed that EE designers have more demanding needs in the use of RM tools in EE design than mechanical designers, and should therefore lead the tool customisation. The same relation goes for the mechanical discipline when it comes to CAD and PDM systems. The approach of Shifting Lead has a strong user focus but must not entirely focus on user needs. Other aspects of PLM introductions also have to be accounted for, e.g. the business needs and the technical challenges, in order to create cost-effective solutions with good integration capabilities. This process can improve both the quality of IS customizations and the satisfaction of the end users, as well as allowing for smart PLM integration.

4.7 Paper G: Measuring IS/IT Performance – A Model to Identify Improvement Areas in Engineering Information Management Based on User Satisfaction

4.7.1 Purpose

The purpose of this paper was to identify improvement areas based on the design engineers' experiences of engineering information management. These measurable improvement areas could then be pinpointed for resource-efficient PLM improvements.

4.7.2 Results

In this paper a measurement model for IS/IT performance based on users' perception of information management is presented. In the survey, IS user data were gathered from engineers which were later analysed with PLS statistical analysis. The questions of the questionnaire are mapped towards different areas with relation to user satisfaction of IS (Figure 33).

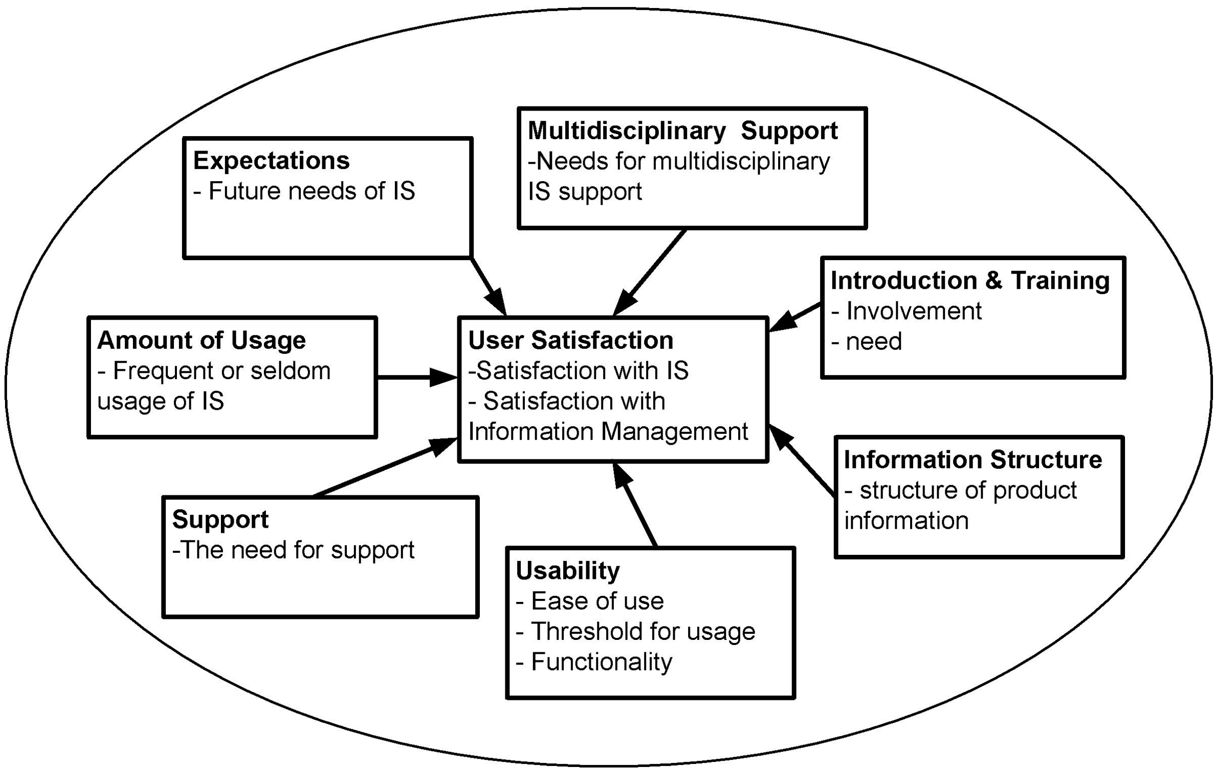


Figure 33. Satisfied users can be created with different focuses.

4.7.3 Conclusions

The analysis resulted in a few modifications of the model. The factor “Multidisciplinary Support” was shown to be a dependent variable. The former factor “usability” was split into two separate factors called “Usage” and “Usability”. Finally, a new factor was added, “Expectations” that contains each IS user’s expectations about the future IS/IT solutions. In order to show the importance of each factor, and the possibility of the factor to affect other issues, the variables have been coloured. Green indicates that that variable has a low improvement potential, while red indicates a large problem. Yellow is somewhere in between, not acceptable but not critical either. The coloured model from the case study is found in Figure 34. Dependences are marked with arrows, and a value for the dependence. Only dependences larger than 10% are shown in the figure, and they are unidirectional.

It is concluded that a survey targeting user needs and benefits makes it possible to:

Identify user (engineers) needs for improved information management.
The use of a survey method enables the company to obtain the engineers’ viewpoints and prioritize towards information management. This is something that can be used to prioritize among IS/IT projects etc. The highest importance for improvements at the studied company lies in the information structure. This is a factor that has a large ability to improve both user satisfaction and the ability to work better cross-functionally. This factor also shows a relationship with the innovation factor. It can further be concluded that the expectations that IS can lead to improvements regarding efficiency and quality are high. There is also a strong belief that IS can contribute to better multidisciplinary support for integration and collaboration:

Provide statistical evidence that shows the importance of improvement of specific areas of a company’s IS/IT environment.
The use of statistical evidence makes it possible to show the importance and the impact of a change towards company goals. Traditionally it has been very difficult to acquire quantitative information regarding improvements in IS/IT.

It is discussed that the survey enables:

Key measurements that can be compared year by year in order to work with continuous improvements.
When several measurements have been done, they can be compared year by year. This is believed to be an efficient management tool in order to see how IS/IT evolves at the company. It will also be possible to detect how changes have affected the experienced efficiency, quality etc. over time.

Benchmarking towards other companies and between different corporate sites.
It will also be possible to evaluate different corporate sites, or different companies with each other. The survey method does not give the answer to what specifically is better or worse at a different site/company, but offers data that can be worked with in order to improve the IS/IT.

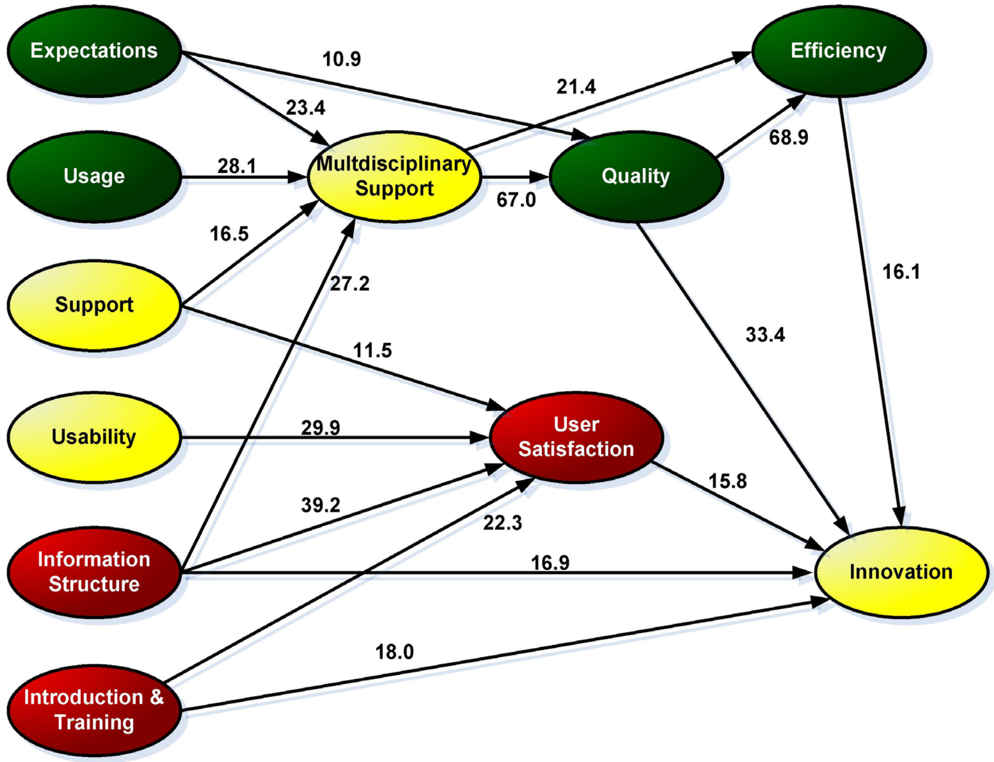


Figure 34. Resulting statistical model

4.8 Paper H: Motivation Mapping Method as Means to Improve Engineering Information Management

4.8.1 Purpose

The purpose of this paper was to develop and evaluate a method for selecting groups of PLM users with similar needs, presumptively in the context of a PLM introduction project. The hypothesis is that users can be grouped regarding their receptiveness to change (Figure 35). The basic assumption of the research is that user dissatisfaction with IS/IT will lead to a higher receptiveness to change, the IS/IT.

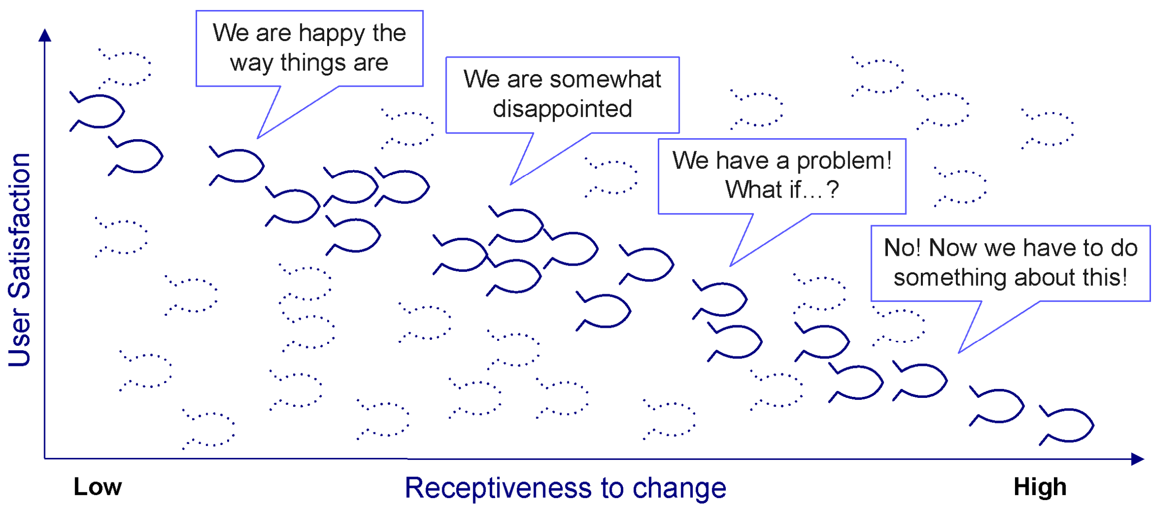


Figure 35. Based on the given hypothesis, the relation between user satisfaction and current IS solution and receptiveness to change is plotted in the figure. The symbols illustrate groups of users. According to the hypothesis, the main number of users is distributed according to the fully lined groups.

4.8.2 Results

The case was based on the same quantitative material as presented in Paper G, but instead of a PLS analysis a cluster analysis of the data material was performed. The idea behind the cluster analysis is to cluster different types of users according to some specific characteristics connected with receptiveness to change. The cluster analysis was based on three factors extracted from the original data material, called satisfaction, experienced benefits and expectations.

In order to get a value for *receptiveness to change* (R), a ratio between Expectations and Benefits was extracted. This ratio indicates that a high value of (R) can be coupled to individuals who have high expectations that future IS solutions will meet their needs, combined with a perception of rather limited benefits from current IS solutions. A formula (2) is stated. The clusters combined with the formula for R are plotted in Figure 36. The size of each group corresponds to the area of the plotted circle. Group 4 is thus the smallest and Group 1 is the biggest.

$$R_{modified} = (E + (11\text{-}B)) / 2. \qquad (2)$$

4.8.3 Conclusions

It was indicated in the results from the performed case study, in line with the hypothesis, that the more disappointed designers feel with their ICT work environment, the more receptive they are to changes made in information management. The most dissatisfied group is also the group that scores the highest receptiveness to change.

Results presented in this paper indicate that user segmentations can be performed on the basis of the expressed levels of satisfaction, experienced benefits and expectations among respondents. The calculation of receptiveness to change has proved to be feasible in an industrial setting, verifying prior qualitative research results. It has also been shown that an estimation of motivation level for each user or group of users regarding adoption of a new ICT can be made.

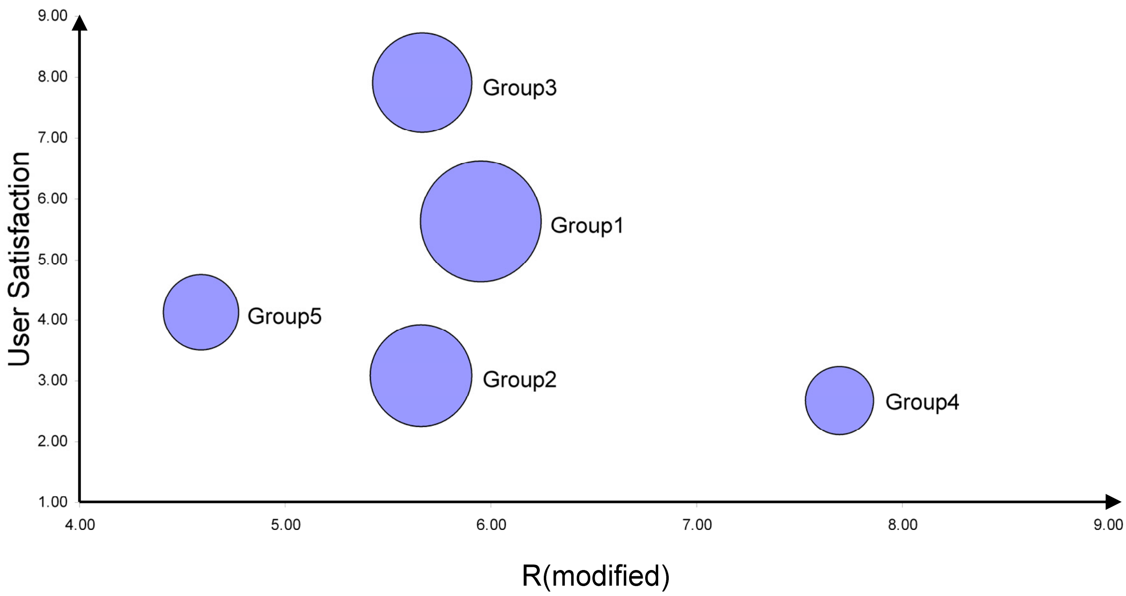


Figure 36. Results of group clustering

5 DISCUSSION OF THE RESULTS

In this chapter the research results are further evaluated. The research questions are reflected upon in an attempt to give answers to them.

The problems with integrating mechatronic product development into PLM systems can be seen from three viewpoints: technical challenges, business needs and user needs (Bergsjö 2007). The technical perspective includes what is technically possible to achieve by purchasing an off-the-shelf product and customising it, or what is realistic to achieve when developing a system in-house. The business perspective concerns the development process, and the traditions of the company as well as the need for integration between departments. The companies' legacy regarding IT and processes is also an important factor to take into the equation; a mechanical focus or an origin in electrical or even software development will affect how the company works. The main foci of the business are profit, cost reduction, customer satisfaction, and efficiency. The third perspective identified is the user perspective, which is what the actual user, the design engineer, wants and needs and is motivated to use regarding tools and systems. User needs play a large role for the individual, as do the technical issues, but have their own unique prerequisites where the usability and functionality of the system are of great importance: will the PLM system actually contribute to facilitating the engineering, increase time for innovation, and improve the speed of engineering changes? Other factors could have a negative impact on the user perspective; for instance, if there have been a lot of organisational changes and system introductions in the past that were not successful, then the presumptive user will probably be more reluctant regarding the introduction or change of a PLM system.

5.1 PLM Implementation and Development

Business needs are the main driver in order to invest in new system solutions for product development. Literature (e.g. (Stark 2005)) regarding implementation of PLM systems in general calls for strong management involvement, to ensure funding and commitment over time. It is therefore essential that a PLM system is adapted to the business needs of the company in order to be successful. This is further supported by Garetti and Terzi (2005) since they claim that PLM projects can be considered as medium-technology-intensive projects, but as a highly intensive challenge regarding organisational issues. Making functionalities such as configuration management and ECM available across all the mechatronic disciplines will make it possible to include software and software components in the platform development. This would facilitate reuse and quality control of software. Empirical findings have shown (Paper B) that data integrity and integration across disciplines are the main PLM driver for the business perspective. These factors are believed to ensure efficiency in the product development and high quality in the product developed.

The results from Paper A show that it is possible with relative ease to modify a commercially available PDM system in order to manage mechatronic data. In the study, however, this was limited to the scope of the PDM system itself, not including the actual information-authoring software, such as M-CAD, E-CAD, and software editors and compilers. Full integration with CAD has been available on the market for a while, and from a technical perspective it is possible to extend this integration to E-CAD (as has been done in some parts already for wiring and allocation of electronic hardware), and to software code and compiled files (Paper A). Paper A concluded that an integration concept based on a service-oriented architecture can include both discipline-specific process support and the cross-discipline information functionality needed in mechatronic development. In the automotive industry, the software is often developed by a supplier, and then only the requirement specifications need to be managed and not the concurrent versions of software. This is possible to do with currently available PLM systems, as shown in Paper A.

Paper D presented a demonstrator that showed the possibility to work integrated and automated with the help of KBE applications in the EC work flows. Paper D showed that it is possible to work with a loose integration concept and manage the complexity. The standard used (PLM services 2.0) helped to manage this perceived complexity. The development of standards and the future use of standards for product data management, integration and communication make it possible to work with loose integrations and SOA. Without the standards, companies would very soon build systems that are even more complicated and more costly to maintain than the current legacy systems which they are trying to replace.

Neither Paper A nor D has been evaluated in a live industrial environment, which means that the results reflect an ideal case, and that many of the difficulties involved in real implementations have been avoided. Nevertheless, both papers show the possibilities of higher automation and integration that are desirable to many engineers. The problems with large and complex organisations are reflected not only by the technical possibilities but also by organisational complexity.

5.1.1 Research Question 1

RQ 1. *How can PLM systems be adapted to better support mechatronic product development?*

Paper C showed that it is technically possible to adapt commercial PLM systems to the needs of mechatronic product development. The problems lie in identifying organisational difficulties and in finding compromises between conflicting requirements. One fundamental technical problem identified in PLM systems is that they do not (in general) support concurrent versioning, which is a widely used function in software development. In order to support software development without major modifications to the core of the PLM software, changes in the software systems engineering process are needed. In the automotive business and at the case company studied, actual software development is performed by suppliers, and the problems connected with managing the requirements of software are not as great as in firms that do actual code development; it is therefore argued that software RM is to some extent performable in current PLM systems. It is not possible to customise the software to fit every individual, and standardisation is therefore necessary. Paper D further elaborated on this question by implementing a loose integration based on PLM Services standard. In this paper it was shown that a flexible architecture can support practically every IT tool possible (simulation software and CAD software was used as an example), since information is packaged and distributed over the Internet and executed in a stand-alone engineering tool.

5.2 PLM Architecture and Integration

When discussing PLM architecture with professionals, it is clear that they express a great need for process and engineering focus. It is, however, popular to focus on IT and IT systems very early in projects. The IT systems and PLM systems part of an overall PLM introduction project is the hands-on work that generates something to show and test, and hence the modelling and mapping of PLM processes and IT architecture are often neglected.

Several approaches to setting up a PLM architecture that enables efficient mechatronic integration were presented in Paper B. In addition to these architectures, the principle of SOA was presented in Paper C, and further elaborated in Paper D. Which architecture to choose is not an easy task for PLM implementors and they have to work with several factors in order to choose the most appropriate PLM architecture. Factors to work with include, for example, the need for and the degree of integration between applications, the amount of people involved in the process, and the current situation (the legacy). For example, a small company could probably work quite efficiently with an all-in-one PLM system, possibly an integrated suite of tools from the same vendor. Since there are not many designers involved in the process and the amount of data is not huge, an installation and migration towards a commercial off-the-shelf product would be quite efficient. A large and complex organisation, on the other hand, which has a large legacy as well as other entities, such as customers and suppliers which it cannot influence, is probably better off with a highly flexible and adaptable PLM architecture, such as the one offered by SOA.

The architecture needs to support several viewpoints regarding both technical and organisational factors (Bergsjö et al. 2008a). These viewpoints include, for example, technical aspects, i.e. how the product is represented in CAD; customer and supplier interfaces and overall architectural aspects, i.e. how workflows for change management and how functions for configuration management are integrated.

5.2.1 Research Question 2

RQ 2. *Which are the architectural needs of integrating IT systems and tools used in mechatronic product development?*

When considering implementation of mechatronic support in PLM systems, the problems are multidimensional – including heterogeneous groups, development tools, and systems. In reference to Paper B and Paper C and revisiting research question 2, an approach that ensures high information management support is essential. To integrate information, making it accessible to everybody who could possibly have use for the information, is not enough; the information itself must be understandable to the user who needs it. A way to manage these synergies and trade-offs is presented in Paper E. Functions that are distributed over several disciplines can be managed by a flexible SOA architecture. Standardised information protocols, e.g. STEP and a clearly defined terminology for the information exchanged as offered for e.g. PLM services (Paper D), would be beneficial in order to manage the architecture and the changes to the architecture over time. Further, means for documenting and controlling the architecture are essential if a flexible integration approach is chosen.

5.3 Organisational Perspectives on PLM

Business needs seem, not surprisingly, to be the focus of most related research. For example, Collier (1999) and Hallin et al. (2003) focus on the information that needs to be available in order to successfully exchange product data within an extended enterprise. Recent standardisation efforts, e.g. ISO 10303, AP 233 and AP 239, show that this subject is highly investigated as well as introduced in industry. The business perspective on mechatronic product information is how to use information management (PLM systems) in such a way as to develop better products and to increase sales. The part that a PLM system can contribute to improving the business is mainly as a facilitator for management of information, including engineering change management and configuration management throughout the extended enterprise. The structured information management is also believed to ensure the product quality, since the information regarding the product and components is ensured to be accurate. As a third factor, efficiency regarding lead-times and process steps can be improved since less time is spent on administrative tasks.

When investigating organisational factors, such as management and user interaction, it is evident that all requirements, both technical and organisational, are difficult to fulfil. Paper E focused on the different conflicts that exist within an organisation and the presumed trade-offs regarding the PLM system that this leads to. However, it was found in Paper E that there exists a large amount of synergies within the organisation on all levels, which could also be in focus. The focus on the positive effects of PLM rather than the more difficult aspects would make it easier to introduce PLM in a way that is more easily adopted by the organisation. The main trade-off, or difficulty regarding PLM, was found in the conflict between the users' need for "domain-specific IT tools" and many management needs (Table 2). This problem could to some extent be managed by the implementation process presented in Paper F, the Shifting Lead approach. By using this approach, each engineering tool would be stepwise integrated towards the core PLM system, utilising a process that prioritises implementation according to the development group with the highest need for integration. This process could then be enriched with the statistical approach presented in Paper H in order to identify the group with the highest need.

The user-related challenges are mainly brought up in Papers E and F. It was shown in the case study performed that the designers did not work efficiently with information management. Efficiency would probably be the greatest achievement of a PLM system, to make the engineers stop "shovelling gravel" (meaning doing unnecessary work, over and over) as expressed in one of the interviews (Bergsjö and Malvius 2006). In order to motivate and promote the use of a PLM system, it is not sufficient to show PowerPoint slides – it has to be proven that the new system actually can improve the conditions and release time for more important activities, such as being creative and inventing new products. Malvius et al. (2006) showed that a small-scale bottom-up approach in introducing an RM tool is possible, and that success can be achieved by small means in a small group where the user perspective is the leading focus. However, the benefits from an overall business and organisational perspective are debatable, since information cannot easily be shared outside the specific group. Further, regarding the organisational impacts of user needs, when comparing the user-need aspect to general product development theories (e.g. Andreasen 1980), it is shown that the need is the basis of any product development project. Moreover, Ottosson (1999) states that the user (not necessarily the buyer) should be the main focus of a product development project. Transferring the same thinking to a PLM introduction and adaptation process should put the user and the use of the PLM system in focus. Doing this should make the PLM suppliers create PLM systems that are appreciated by the intended user, and not focus so much on the paying customer (the business perspective). In the end, a happy user will be appreciated by the business and hence be willing to pay more for such a solution concept.

5.3.1 Research Question 3

RQ 3. *What are the organisational aspects, focusing on user and management view, of PLM system support and PLM introductions?*

Papers E and F and research question 3 made it clear that, even though designers often focus on their own work at hand, they have a need for information integration and easy exchange of information. Usability issues involve reducing the burden of administrational tasks, as discussed in Paper E. An SOA approach that is discussed in Paper C enables engineering disciplines to keep a large degree of independence from the integration layer, allowing a higher degree of uniqueness, as for example is the current state of practice in software engineering.

There are, however, problems with too strong a user focus, i.e. a complete bottom-up approach. A pure focus on the user would result in highly customised one-of-a-kind applications that are difficult to maintain and to integrate with other information management systems.

From the case studies presented in Paper G, it was shown that the users are in need of structured information and that this is the main issue to improve regarding the information management. Further, Paper E showed that the users and management did not use the same terminology or focus on the same benefits regarding the implementations of PLM. This is important for management to know when rolling out a new PLM system, in order to motivate the PLM users with terms that they connect to positive effects.

5.4 Management of PLM introduction and improvement

In order to successfully show the potential benefit of an improvement, it is a common industrial practice to present some kind of evidence or business case for management. In large and complex organisations where several projects compete for a limited budget, this is exceptionally important – if you cannot demonstrate the benefit with credible figures, you are unlikely to obtain funds for something that is important. So far there has been a lack of competent management tools that could measure the potential improvements to the process and IT landscape, and most predictions have been based on assumptions and a few qualitative estimations (Malvius et al. 2008). The method Presented in Paper G makes it possible to measure information management areas by using a questionnaire sent to all users within the organisation. The results can then indicate where the users have the largest problems and then where funds should be prioritized. Paper H also uses statistical analysis, but in this case in order to identify groups of users with particular needs towards PLM. Both methods make it possible to give management a fair estimation of the current situation of the company and different entities that is statistically reliable.

It is important to develop measurements that reflect the actual need of the organisation and that are important to measure and that promote efficient development. The measures presented in Papers G and H are not by themselves complete, but must be used together with existing management tools. These measures are tools that help the management to extract the organisational needs and requirements on the corporate PLM. The intent is to give management a more complete picture especially regarding the needs of the PLM users. This perspective is otherwise often neglected since it is difficult to assess. PLM vendors more often focus on functionalities and technical details rather than large organisational gains with PLM, since these are abstract and difficult to assess. However, the approach presented in Paper G could presumptively be used to measure improvements over time, and could thus give an indication of whether or not a change actually results in an improvement for the PLM users.

5.4.1 Research Question 4

RQ 4. *Could management methods and tools that take in the user perspective support the introduction and the improvement of a PLM system?*

The user perspective can be considered from several aspects, both qualitatively and quantitatively. This research has primarily used two different tools that could be used by management: a qualitative approach by using interviews, and mapping different needs in order to find conflicts and synergies (Paper E). Secondly, a quantitative tool based on a survey approach and statistical analysis has been presented in Papers G and H. In particular, the method presented in Paper G is of interest for management since it identifies the areas which are in greatest need of improvement according to the design engineers.

The tools presented can be used in combination with other tools to assess business needs, improvement areas, and PLM users with similar needs. This could benefit management for decisions regarding PLM implementation, when to implement, where the highest needs are, and who are most likely to adopt the PLM solution.

5.5 Goal Fulfilment

Regarding the goals stated in Chapter 1.2 it can be said that this research has fulfilled the major part of these goals.

- *Investigate differences and similarities between mechatronic disciplines (software, electronics and mechanical engineering), in their view on PLM, from a user and management perspective.*

This has been done within most papers, especially Paper E which focused on the PLM user and management, and found that the view on PLM differs depending on organisational belonging.

- *Evaluate the possibility of mechatronic product data integration in commercial off-the-shelf PDM systems.*

This has been shown firstly in Paper A in a closed commercial PDM system, and then more elaborately with the use of standards in a SOA in Paper D. It can therefore be stated that this is possible, but that it is more important to focus on integration via open interfaces rather than on what is possible within the commercial off-the-shelf softwares themselves.

- *Evaluate and test architectures for how to achieve mechatronic product data integration in PLM systems.*

A thorough evaluation of architectures is presented in Paper B. This has been expanded and tested in Papers C and D. Results show that flexible integration concepts are more promising than the traditional consolidation strategy known as single-source (or all-in-one) integration.

- *Evaluate the possibilities with a loose integration concept such as that offered by a service-oriented PLM architecture.*

This was proposed in Paper C and successfully demonstrated in Paper D. The major advantages were found in the flexibility of the integration and hence the possibility to expand and change over time.

- *Develop tools to better manage the user perspective of a PLM system introduction.*

This discussion is started in Paper E and continues in Papers F, G and H. Paper E suggests an introduction strategy based on the PLM users' need for PLM. This is further supported by the statistical method presented in Paper H, a method that can be used to find the PLM users with the largest need for PLM.

- *Develop tools to better manage the user perspective of PLM and to assess and prioritise improvement of the PLM system.*

A categorisation matrix is presented in Paper E that can be used to find goals and needs that are common throughout the organisation. The statistical method presented in Paper G can be used to identify and prioritise the PLM users' current problems with PLM, and to associate them with corporate benefits.

5.6 Contributions

This research and the thesis have contributed to showing that it is possible to implement and improve PLM for mechatronic development concerning architectural and organisational perspectives. The following contributions of each paper show a high degree of novelty, particularly within the PLM research field.

Paper A: Showed that it is possible, in both advanced and basic PLM (PDM) systems, to manage requirements, functional dependencies, and mechatronic components. This has not explicitly been shown in related research.

Paper B: Presented, and summarised in available literature, architectures for SCM and PDM integration. A discussion regarding user and business needs contributed to greater knowledge of the trade-offs between standardisation and customisation of PLM systems.

Paper C: Analysed loose integration concepts based on a service-oriented architecture, and contributed to the theoretical applicability of concepts for multidisciplinary engineering, including engineering change management and configuration management. Unique empirical material from two large independent automotive manufacturers was used to strengthen the arguments.

Paper D: Demonstrated new approaches to use Service Oriented Architecture on automated engineering change management. The paper further contributed by evaluating the emerging new PLM Services 2.0 standard.

Paper E: Identified problems regarding organisational goals, need and benefits of information management support. Further, an approach was presented to identify and manage the conflicting views of the organisational units.

Paper F: A new introduction strategy based on the needs and motivation of each engineering group was presented. The novelty of the approach is that different groups are prioritised according to their needs and that the group with the highest needs is permitted to define the requirements in a PLM introduction project.

Paper G: A new approach using advanced statistical tools for identifying areas with high improvement potential regarding the user perspective was identified. Quantitative data collection makes it possible to base decisions regarding PLM implementation and improvement projects on reliable statistics. This is a new approach within the field of PLM.

Paper H: A new statistical tool based on cluster analysis was used to identify user groups with similar needs. This new method makes it possible to facilitate a PLM introduction by focusing on the need of each group. Statistical information makes it possible to decide which groups are likely to be quick adopters or vice versa when considering a PLM implementation project.

6 VALIDATION

In this chapter the research results, approach and validation are discussed. The applicability of the results, the validity and the methodology are reflected upon.

6.1 Discussion of Research Approach

The research approach taken, involving interviews, quantitative data collection, seminars, document review, and demonstrators, reflects a broad research scope. Open-ended interviews have made it possible to discover problem areas that otherwise would be difficult to find. The perspectives of people within large companies, small companies and different hierarchical levels differ, which makes it important to gather this different knowledge and information about problems and challenges to the work with PLM. The quantitative study (Study 5) further made it possible to quantify and statistically measure and further evaluate the qualitative findings, giving the qualitative research results a quantitative verification.

The seminars and workshops conducted made it possible to discuss the results, as well as to gain feedback on the research results. Seminars within an industrial setting made it possible to explain the results from the participating companies' perspectives and to discuss solutions and challenges on a higher level. Seminars within research and academic settings made it possible to discover relevant input from other studies and related research.

The development of demonstrators made it possible to show that the theories and methodologies created actually work and can be implemented in engineering-like environments. The feedback from the demonstrators gained during the seminars and workshops made it possible to further develop the demonstrators. These prototype solutions, however, are far from the real industrial implementation settings, and these simplifications are important to note when talking about the applicability of a demonstrator.

A shortcoming of the research is that it is difficult to know what PLM suppliers and leading manufacturing firms (outside the scope of the research project) have planned for and are developing right now. Information available is mainly restricted to currently available commercial solutions, and the IT tools and systems of the participating companies. With mainly a single industrial partner and automotive focus, it is also difficult to assess the whole PLM market. The focus on PLM, in the sense that computers should manage the information, might be shown to be wrong; perhaps a focus on the information itself, or more focus on the work procedures and development processes, would have led to a different result. The focus has been on PLM and its predecessor PDM, whereas a focus on other computer systems, e.g. RM or ERP, could have yielded different conclusions.

6.2 Verification and Validation

There are two major ways of verifying the validity of a design research study: logical verification and verification by acceptance (Buur 1990). The strongest piece of evidence for validity and trustworthiness of this research is the interest experienced in industry. The automotive partner involved in this research has recognised the applicability of the research results, and the fact that it has gained knowledge and improved its possibilities of stating requirements towards future PLM systems. Whether the results applied in this thesis are valid in a more general setting is difficult to answer at this stage. Another sign of validation of the work is the interest shown by the engineers at the participating companies, expressing their need for better information management solutions.

Going back to the validation square, in Chapter 2, the validation can be discussed from the following four views:

Theoretical structural validity: *Correctness of constructs, both separately and integrated. E.g. consistency of theory in phenomena modelling, similarities and applicability to mechatronic data representation.*

This research is based on other research, as presented in the Frame of Reference chapter. The information models used for implementing mechatronic support have been based on research within the field of information modelling. E.g. the information model used in Paper B was based on previous research (i.e. Collier 1999; Andersson et al. 2002). The statistical approach used in Study 5 is based on accepted statistical methods, and has been used in similar settings for calculating satisfaction of bank customers (Eklöf 2006). No deviation between the research results and the frame of reference has been discovered.

Empirical structural validity: *Appropriateness of example problems (case studies) and the usefulness of the method applied. E.g. industrial projects where highly advanced mechatronic product development (systems engineering) can be studied.*

Study 1 and the case studies behind Papers A and B were carried out both in the automotive industry in EE development and at a smaller manufacturer of test equipment. Both products were highly complex and, reflecting upon the cases, it can be stated that both case studies were relevant for testing the applicability of an integrated information model for mechatronics in PLM systems. Further validation was brought to this project when a second independent German automotive firm was involved in Study 2 together with the Swedish firm. The studies 3-5 all reflected the mechatronic aspects of the systems engineering process in EE development at the same Swedish automotive firm as in Study 1 and 2.

To gain further structural validity, other branches of industry could have been more involved in the research work than currently is the fact. For example, businesses in the telecom sector or home electronics sector are most likely to have similar problems regarding mechatronic development even though this has not been highlighted by the case studies.

Empirical performance validity: *Performance of the solutions with respect to the example problems. E.g. the measured performance according to fewer errors (higher information accuracy), reduced lead time in product development.*

Papers A and D show the possibility to assess performance regarding introduction of support for mechatronic PLM. The problem with the results from Papers A and D was that the demonstrators were not implemented in a setting that could be comparable to a full-scale scenario in industry. In Paper D it is evident that the approach would lead to higher efficiency since manual steps are automated. With the approach taken it takes about 10 seconds to perform an engineering change and simulation, where a manual change would take significantly longer. Thus this part of the validation square is difficult to validate using before-and-after figures, even though many of the results are in the direction of being able to offer higher performance as pointed out in e.g. Paper C.

The management tools presented in Papers G and H have to a large extent been confirmed as being able to identify the right problems and problem areas. However, this has been done in a qualitative way by discussion in groups with company experts. The possibility of making measurements before and after a PLM introduction with the method presented in Paper G could have generated performance validity for the research project. But this has not been possible to perform within the limited time of that research project, and due to the fact that a PLM for mechatronics system was never introduced during this time period.

Theoretical performance validity: *Performance of the method beyond the example solutions. E.g. transferability of the specific case to other cases. Systems engineering in the automotive industry in general, applicability to other industries.*

It is believed that the results of this research are generally applicable to all industries developing mechatronic products. An assumption is that they are fairly large, or with a number of complex relations which are not possible to manage for a small team. The applicability of the PLM for mechatronics approach in the small firm as well as the large firm (in Paper A), besides the differences of the products, supports the idea of the research being generally applicable. Further validation of this are the similarities discovered between the two independent automotive firms, and their common need for PLM, as discussed in Paper C.

The matrix (Table 2) used in Paper E is generic and the same approach could easily be applied to other manufacturing companies. This is also true for the questionnaire used in Study 5 (Papers G and H). The questions are deliberately generic and could be adapted for use at other companies.

7 CONCLUSIONS

The conclusions of this research are presented here.

The performed research has contributed to the research community with tools and methods regarding PLM architecture development and means to involve the PLM user in the PLM for mechatronic development. The main conclusions are presented according to the topics of the research questions.

7.1 PLM Architecture and Development

PLM architecture, i.e. the way the processes, information and IT systems are organised within a company, is of utmost importance in order to achieve effective mechatronic product development. This has been shown in the research by performing case studies, testing PLM systems, and assessing different integration technologies both in theory and in practice.

From the research it can be concluded that:

- A complex organisation benefits from a flexible PLM architecture that can be upgraded and changed over time. A service-oriented PLM architecture is one technical solution that offers this flexibility.
- A flexible architecture makes it possible to introduce and phase out IT systems and applications continuously.
- A SOA-based architecture enables every business to focus on its processes, and not to have rigid processes programmed into its IT infrastructure.
- SOA offers more flexible interfaces towards downstream applications, and allows integration of applications that are not designed to be integrated towards each other.
- It remains a challenge to fully manage software development within a PLM system.
- Version management can be achieved between mechanics, electronics and software by using a PLM system, if current state-of-practice mechanical versioning is sufficient.
- Simplified engineering change management can be conducted for mechatronic products in a PLM system.

7.2 Organisational Perspectives on PLM

When stating requirements on a future PLM solution and later on when introducing the system to the organisation, it is extremely important to include the organisation, especially the perspective of the users (design engineers). Top management commitment and a combination of top-down and bottom-up approaches are other aspects that are important in order for the organisation to quickly adopt new PLM systems.

From the research it can be concluded that:

- From the users' perspective, mechatronic full-integration concepts would in most cases require changes to their discipline-specific development process in order to adapt to work procedures that are standardised across disciplines.

- Access to integrated information and better management functionality would reduce the time that users spend on administrative tasks. Higher efficiency in the information management could release time for more actual design work (innovation, improvements, etc.).
- It is possible to identify different organisational drivers from a management and a user perspective. These drivers can then be mapped towards each other in order to identify synergies and necessary trade-offs. Examples of such synergies are higher quality and efficient information retrieval, which have no internal (management vs. end user) conflict.
- It is possible to use statistical methods based on a quantitative approach to identify problem areas within PLM. This result is presumed to be usable to prioritise PLM projects and to evaluate improvements. In the case study performed in the automotive industry, the need for information structure was found to be the area with highest priority.
- It is possible to identify PLM users with similar needs for PLM usage. This result is believed to be usable when selecting pilot project groups, for stepwise PLM introduction, and for distributing educational resources.

8 FUTURE WORK

This chapter presents suggestions for further research within PLM.

Regarding development and integration of PLM systems for multidisciplinary use, some key work remains to be done. The mechatronic integration in PLM systems is not complete, especially when it comes to integration between software and mechanical engineering. As long as the actual programming and compilation of software are performed in an external tool, the management, version and configuration can be managed in the PLM system. Future studies will have to show how far the integration is beneficial.

One way to allow partial and stepwise integration in product development is the service-oriented PLM architecture. This approach, however, faces many challenges regarding management and governance. Future studies will have to evaluate these problems and find solutions for management and documentation of SOA over time. It is also of interest to evaluate the standard PLM Services as it evolves and (if possible) is accepted by industry.

The Shifting Lead method has not been tested in a real PLM implementation project, and it would be interesting to do so – preferably in combination with the statistical methods for clustering PLM users.

Future studies can validate the statistical management tool used in Paper G, by performing the study at other companies. The questionnaire can also be refined to incorporate (and test) other factors' impact on the PLM user satisfaction.

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