TAMPERE UNIVERSITY OF TECHNOLOGY

VILLE VAINIO

COMPARATIVE RESEARCH OF PLM USAGE AND ARCHITECTURE

Master of Science Thesis

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TIIVISTELMÄ

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Tuotteen elinkaaren hallinta (PLM) on strateginen liiketoimintatapa, joka tukee tuotteen määrittelytiedon hallintaa läpi koko tuotteen elinkaaren. PLM:n toteutus on nykyään keskeinen vahvuus jokaiselle valmistavan teollisuuden yritykselle.

Tässä diplomityössä tarkastellaan PLM-järjestelmien toteutusta, arkkitehtuureja ja ohjelmistojen välisiä integraatioita. Työn tavoitteena on selvittää järjestelmien arkkitehtuurin ja käytön suhdetta. Toisin sanoen tässä tutkimuksessa pyritään ymmärtämään reaalimaailman ilmiötä vertailemalla havaintoja case-yrityksistä kirjallisuudessa esitettyihin malleihin.

Diplomityö muodostuu kahdesta osasta. Kirjallisuuskatsauksessa arvioidaan tuotteen elinkaaren hallintaan liittyviä osa-alueita. Aluksi käsite PLM määritellään, minkä jälkeen tarkastellaan syitä PLM:n käyttöönotolle, PLM-järjestelmille asetettuja vaatimuksia, käytössä olevia alijärjestelmiä sekä PLM:n kypsyysastetta ja arkkitehtuurimalleja. Kirjallisuuden pohjalta muodostetaan nelitasoinen kypsyysmalli ja tunnistetaan kolme keskeistä järjestelmäarkkitehtuurityyppiä: legacy, single source ja service oriented -arkkitehtuurit, joihin keskitytään tässä tutkimuksessa.

Tutkimuksen empiirisessä osassa analysoidaan kuutta suomalaista valmistavan konepajateollisuuden yritystä vertailemalla niiden tuotteen elinkaaren hallinnan kypsyysasteita ja järjestelmäarkkitehtuureja. Kunkin yrityksen PLM-kypsyyttä arvioidaan kirjallisuudessa esitettyjen mallien pohjalta. Arkkitehtuuri- ja integraatiotyypit määritellään jokaiselle case-yritykselle erikseen. Kirjallisuudessa esitetyt eri arkkitehtuurityyppien vahvuudet ja heikkoudet havaittiin toteutuvan myös reaalimaailman tapauksissa.

Tutkimuksen aineisto koostuu materiaaleista, jotka kerättiin kuudessa suomalaisessa yrityksessä järjestetyissä alkukartoituksissa ja benchmark-vierailuissa. Kyseiset yritykset ovat mekatronisten tuotteiden valmistajia ja ne toimivat maailmanlaajuisissa valmistusverkostoissa.

Tässä tutkimuksessa havaittiin, että PLM:n kypsyysaste ja järjestelmäarkkitehtuurimallit ovat yhteydessä tuotetiedon käytön ja hallinnoinnin tehokkuuteen. Huolto- ja projektiliiketoiminta osoittautuvat tuotteen elinkaaren hallinnan kannalta haastavimmiksi alueiksi, mikä johtuu siitä, että PLM-järjestelmien käyttö keskittyy elinkaaren alkuvaiheeseen. Tulevaisuudessa ohjelmistojen ja järjestelmien toivotaan tukevan entistä paremmin myös elinkaaren lopun ja erityisesti keskivaiheen toimintoja.

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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Product Lifecycle Management (PLM) is a strategic business approach which supports the management of product definition information throughout the product lifecycle (PLC). Implementation of PLM is becoming a crucial asset for any manufacturing company.

This thesis examines PLM systems regarding the implementation, system architecture and integrations between the tools within. The main goal is to clarify the relation between the architecture and actual system usage. In other words, the research seeks a better understanding of a real business phenomenon by comparing discoveries from case companies to the models presented in literature.

The thesis is divided into two parts. In the literature study, several PLM related aspects are evaluated extensively. Starting from the definition of PLM, reasons for applying it, the different requirements for a solid PLM system, the subsystems used and moving on to the PLM maturity and architecture models. A four level maturity model is put together and three dominant architecture types, namely legacy, single source and service-oriented architecture, will be focused on in the study.

In the empirical part of the research, six Finnish manufacturing companies are analyzed and compared regarding PLM related maturity and system architecture. The level of maturity is compared to the models presented in literature. Architecture and integration types are defined for each company. The strengths and weaknesses of each architecture type defined in the literature study part are proven to be accurate also in actual cases.

The analyzed data was gathered from pre-surveys and benchmarking site visits which were conducted in six Finnish companies. These companies are original equipment manufacturers of mechatronics products in Finland, but they operate in global manufacturing networks.

The study indicates that the PLM maturity level and architecture models are closely related to the effectiveness of usage and management. Service and project business seem to be the most challenging fields in PLM. This is because PLM systems are mainly used in beginning of life activities, but in the future also the end of life and especially middle of life activities will be receiving more support from the tools and software.

PREFACE

This Master of Science Thesis was done at the Department of Production Engineering at Tampere University of Technology as a part of the research project FUDGE. The department and the project consortium are gratefully acknowledged for funding this work.

I would like to thank Professor Asko Riitahuhta and Associate Professor Antti Pulkkinen for the supervision of my thesis. I am grateful to all the people involved in FUDGE, especially the ones who have provided the research material and the ones who have commented and helped with my thesis.

Above all, I want to express my gratitude to my family and my closest friends for supporting me throughout my years at the university.

Tampere, July 26, 2012

Ville Vainio

CONTENTS

ABBREVIATIONS

API	Application Programming Interface
APS	Advanced Planning System
BOL	Beginning of Life
BOM	Bill of Materials
CAD	Computer-aided Design
CAE	Computer-aided Engineering
CAM	Computer-aided Manufacturing
CAP	Computer-aided Planning
CAx	Computer-aided Technologies
CRM	Customer Relationship Management
CRP	Capacity Requirement Planning
EDM	Engineering Data Management
EOL	End of Life
ERP	Enterprise Resource Planning
ESB	Enterprise Service Bus
FEM	Finite Element Method
FUDGE	Research project: Future models for Digital and Global Extended enterprise
ICT	Information and Communications Technology
IT	Information Technology, see ICT

MOL	Middle of Life
MRP	Material Requirements Planning
MRPII	Manufacturing Resource Planning
OEM	Original Equipment Manufacturer
PDA	Personal Digital Assistant
PDKM	Product Data and Knowledge Management
PDM	Product Data Management
PEID	Product Embedded Information Device
PLC	Product Lifecycle
PLM	Product Lifecycle Management
PPR	Product, Process and Resource
RFID	Radio Frequency Identification
ROI	Return on Investment
SCM	Software Configuration Management
SOA	Service-oriented Architecture
STEP	Standard for the Exchange of Product Model Data
UPLS	Ubiquitous Product Lifecycle Support System

TERMS AND DEFINITIONS

Architecture	Framework for structuring information flows and integrations between systems
As-is	Term referring to an item, process or business model in its present state
Data	Unprocessed and unorganized facts
Data model	*See Information model*
Data vault	Logical data storage used to store and organize documents and files electronically
Database	*See Data vault*
Extended enterprise	Business unit that consists of a company and its suppliers
Implementation	Execution of a plan or realization of an application
Information	Processed and organized data
Information model	Logical organization of objects, their constraints and relationship between them
Integration	Linking together different computing systems
Interoperability	The ability of systems to exchange information and use the exchanged information
Knowledge	Evaluated and organized information that can be used in problem solving processes
Knowledge management	Collection of processes to create, disseminate and utilize knowledge
Lifecycle	All the phases affecting a product, from design and development to retirement and recycling

Middleware	Software layer which provides interoperability functions between systems
PLM backbone	System which functions as the foundation of a PLM architecture
Repository	See *Data vault*
To-be	Term referring to an item, process or business model in its planned future state

1. INTRODUCTION

1.1. Background of the research

Products have become more and more complex after the industrial revolution took place during the 18th and 19th century. This has led to a vast amount of knowledge, information and data to accumulate during the product development and production processes. Companies are making products which consist of tens of thousands of, or even more, different parts like screws, bolts, springs, cables and bearings. The need to organize all this data, along with the new possibilities offered by modern day computing, has resulted in introduction of various product data management practices throughout the product's lifecycle.

This thesis is a part of a Finnish Funding Agency for Technology and Innovation (TEKES) funded research project Future models for Digital and Global Extended enterprise (FUDGE). The project consortium consists of leading Product Lifecycle Management (PLM) professionals from research organizations, system administrators from global original equipment manufacturers (OEMs) and system software vendor representatives. Tampere University of Technology's Department of Production Engineering is one of the three research organizations involved in the project, the others being VTT and University of Vaasa.

The research and this thesis are based on data and information gathered from pre-surveys and benchmarking visits to six global Finnish enterprises. These companies are global original equipment manufacturers of mechatronic products. The project focuses on not only the companies, but also their extended enterprises. Childe (1998) defines the extended enterprise to be a system or a conceptual business unit that consists of a company and its suppliers who collaborate to maximize the returns to each party involved. This means that the PLM usage extends from the company in question to its subcontractors and other partners.

The objective of the Fudge research is to study what kind of information models and business processes best support the product lifecycle management. The project will produce new information of PLM and other ICT system requirements and utilization (Riitahuhta et al. 2010). In order to create and develop future models and tools, the current state with its challenges and possibilities needs to be charted.

1.2. Research material and method

This thesis will study the case companies' Product Lifecycle Management (PLM) architecture, compare different integration types between the systems and in relation to the system usage. In the context of this thesis, the architecture is broadly divided into four separate subsystems: CAE, EDM, PDM and ERP. Computer-Aided Engineering (CAE) is an umbrella term for software used in the design engineering and manufacturing engineering functions (Stark 2004). The CAE data is usually stored in Engineering Data Management (EDM) systems, which are usually tightly integrated to the CAE software. From the EDM the finished designs and product structures are transferred to Product Data Management (PDM) systems. PDM is defined by PLM Interest group (2012) as the IT platform for PLM. Enterprise Resource Planning (ERP) system is used to store manufacturing and production data. The division is not definite, as for example PDM and ERP might share some functionalities and store similar data. These systems are introduced more thoroughly in chapter 2.4.

Literature will be reviewed extensively concerning several areas of PLM. Starting from the definition of PLM, reasons for applying it, the different requirements for a solid PLM system, the subsystems used and moving on to the PLM maturity and architecture models. A four level maturity model will be put together and three dominant architecture types, namely legacy, single source and service-oriented architecture, will be focused on. The case companies' current (as-is) and future (to-be) PLM conditions are evaluated and compared to the literary models and studies. The amount and quality of the data gathered varies between the companies and thus some aspects are discussed more than others.

The research is empirical, as it is based on observing real life phenomena. This thesis uses a qualitative research approach. The primary aim is to comprehend the research subjects, instead of trying for example to solve a predefined problem. This approach is typical for researching questions regarding the internal actions of a company, meaning that the research problems are tied also to employees and their objectives instead of just hard measurable facts (Olkkonen 1993).

The data used was mainly gathered in six site benchmark visits to companies part of the FUDGE project consortium. Additional information such as pre-surveys, company presentations and PDM database query results was also used to expand on the research. For example the stage of the PDM implementation is defined for individual companies based on the benchmark site visits. PDM implementation stages are defined by evaluating maturity models in the literature. These models are introduced in chapter 2.6.

1.3. Research objectives and scope

The main research question, w*hat is the relation between the PLM architecture and the system usage,* is formed by combining the three sub-questions below.

1. What does the PLM architecture consist of and how are the systems integrated?
2. How do the differences in company needs and business context affect the application of PLM?
3. How do the shortcomings in the information systems impact the effectiveness?

The thesis is written using the IMRAD structure. IMRAD is an abbreviation of Introduction, Method, Results and Discussion (Day 1989). Following this introduction chapter, chapters 2 and 3 consist of a theoretical overview of the product lifecycle (PLC), the ICT systems used in PLM, the PLM maturity models and finally system architecture integration and implementation models and approaches. This PLM landscape analysis will form the basis for analyzing the data from the case companies.

The research material and how it was gathered and used is presented in chapter 4. The research methods chosen for this research will be discussed in the same chapter. In other words, this chapter will answer the questions when, where and how the study was performed. Results in chapter 5 will tell the reader what was found in the study. In this chapter all the companies are evaluated regarding PLM maturity, IT architecture and integrations between the systems. In Discussion, the sixth chapter, the research questions and how they were answered are discussed. Conclusions in chapter 7 show the contribution of the thesis by presenting the main results and their meaning. The structure of the research is illustrated in Figure 1.1.

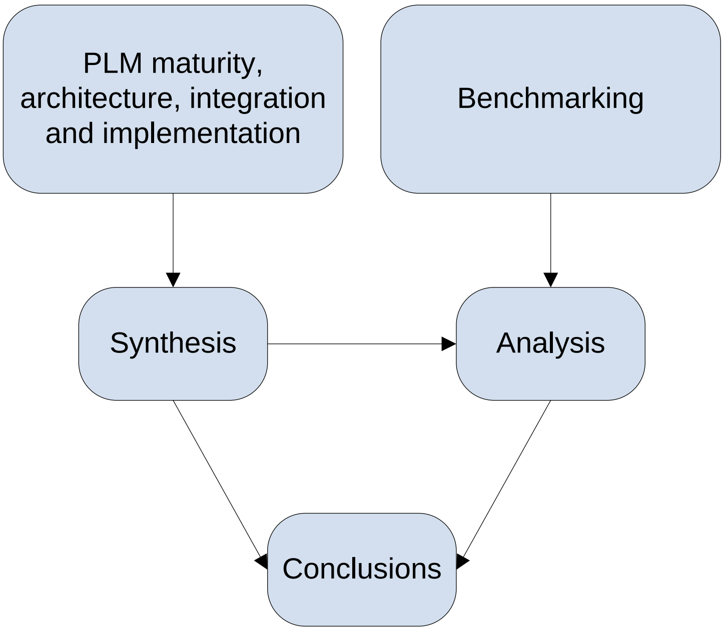

Figure 1.1. *The structure of the research.*

The thesis is based on a literature review concerning PLM maturity, architecture, integration and implementation. A synthesis of these subjects is used together with the material collected in the benchmarking sessions to form an analysis of the state of PLM in the case companies. Final conclusions derive from both the theoretical synthesis and the analysis of real world phenomena.

2. PRODUCT LIFECYCLE MANAGEMENT

2.1. PLM definition

Product lifecycle management (PLM) is a relatively new term, which means that there is no universally accepted way of describing it. This means there are several definitions for PLM. Stark (2004) defines PLM as the activity of managing products effectively across their lifecycle. According to CIMdata (2011), which is a global PLM consulting firm, PLM is a strategic business approach, which applies business solutions, collaborative creation, management and dissemination of product definition information throughout the product lifecycle (PLC). Product lifecycle from the manufacturer's viewpoint is defined by Stark (2004) to include five phases: imagination; definition; realisation; support; retirement. PLM spans through all these phases and integrates people, business systems, processes and information (CIMdata 2011). The main feature distinguishing PDM and PLM is that the latter is intended to manage the product both inside and outside of an organisation (Mostefai et al. 2005). On the other hand, PLM Interest Group (2012) defines PDM as the IT platform for PLM.

PLM supports the whole extended enterprise, which includes for example customers and supply partners. It spans from the early stages, meaning the conceptualization and innovation, to the end of the lifecycle of the product. Product lifecycle management integrates people, processes, business systems and information through a common body of knowledge (CIMdata 2011; Ameri & Dutta 2005). The people who develop the final product can be geographically and corporally scattered because of the involvement of the extended enterprise constellation (Bergsjö et al. 2008).

Mostefai et al. (2005) argue that different data types and formats associated to various applications need to be integrated correctly in a PLM vision. In their 2005 journal paper they express the need for methods to organize, store, access, convert and exchange these data correctly and seamlessly. To generalize, the idea behind PLM is to serve up to date information in a secure way to everyone who is a part of the product lifecycle. Security is achieved by for example restricting access by user types or groups. Information is produced by a variety of actors at different levels of detail in diverse functions inside and outside the company (Terzi et al. 2010).

According to Abramovici and Sieg (2002), PLM is the extension of PDM towards a comprehensive approach for product-related information and knowledge management within an enterprise, including planning and controlling of processes that are required for managing data, documents, and enterprise resources throughout the entire product lifecycle. Knowledge management is described by Ameri & Dutta (2005) to involve three, sometimes interchangeably used, concepts: data, information and knowledge.

Data is defined as to represent unorganized and unprocessed facts. Information is an aggregation of processed data which can be used to ease decision making. Finally knowledge is evaluated and organized information that is purposefully usable in problem solving processes. As the complexity of the concept increases when going from data and information towards knowledge, the former ones are easier to store, describe and manipulate than knowledge. (Ameri & Dutta 2005). As the knowledge usable for problem solving processes has a high value for the companies, generating structured knowledge is one of the critical steps of knowledge management within PLM. PLM also improves the learning capacity of an organization and thus increases the rate of knowledge accumulation. (Ameri & Dutta 2005).

2.2. Reasons for PLM

Depending on the field of business, companies can make use of PLM in different ways. The product could be for example a complex long-life manufacturing object, a complex short-life manufacturing object, a pharmaceutical specialty, a building or a fashion garment (Terzi et al. 2010). For example the aerospace industries' products have long lifecycles, high complexity and physical prototyping is hardly possible. The situation is usually the opposite in electronics goods such as mobile phones (Abramovici and Sieg 2002). Each industry has its own requirements for PLM and different drivers for system introduction as the business processes vary.

One of the objectives of PLM is to integrate applications across the product life cycle and the ability to manage information in a non-redundant and consistent way (Abramovici and Sieg 2002). Product information is scattered among various actors who have their own competences and conception of the product and its performance (Terzi et al. 2010). General benefits strived for include for example lead-time reduction, prototype cost reduction, increase in reuse of components and reduction in late product changes (Crnkovic et al. 2003). In order to be competitive, companies have to manage their value chains effectively to reduce lengthy product development cycles and development costs while simultaneously improving product quality (Terzi et al. 2010).

According to Ameri and Dutta (2005) product innovation and customer intimacy together with operations excellence have become the most important areas of focus for corporations that want to gain competitive edge. These measures of success are mainly influenced by the internal dynamics, or internal forces, of corporations. Chapter 2.2.1 offers a compact presentation of these internal forces. Furthermore, universal trends like globalization, environmental awareness, shrinkage in product lifecycle, increase in product complexity and the push into supply chain pose challenges for companies. These external forces will be briefly presented in chapter 2.2.2.

2.2.1 Internal forces

Leading companies are constantly seeking ways of introducing innovative products and services. Innovation relies on creativity, which is most likely to happen in open environments facilitating inclusion of the best ideas. Thus there is a need for an environment which enables creative and collaborative work methods. With a knowledge management system all the product-related knowledge can be systematically shared among knowledge users. (Ameri and Dutta 2005.)

In order to be competitive, maintaining customer satisfaction and loyalty should be a top priority. Customers often expect to buy products that can be tailored or customized for their needs. This is leading to a transition from make-to-stock and make-to-order to mass customization and personalization. Many vendors offer their customers the ability to customize their products based on their desires, thus pulling the customers up in the design process. Learning about the customer's needs and behaviours would help to design products which properly meet their expectations. To ensure a rich and effective communication, there should be a seamless and direct upstream and downstream flow of information between the manufacturer and the customers. As the customers are in close contact with the product, their ideas about improvements for the product can be of significant help in modifying the product features. (Ameri and Dutta 2005.)

Ameri and Dutta (2005) argue that competitive advantage is not deriving only from the individual activities throughout the value chain but also from the linkages among the activities. When focusing on activities, the result is operational excellence as the activity becomes low cost and quick through improvements in the process. When it comes to linking the activities, for example geometric modelling, to others of similar or different types, then the indicators of excellence are qualities like interoperability and usability. In product design the individual tools usually perform the task they are designed for well, but they might fail when operating in a collaborative environment. This leads to a need of interoperability features, which will be discussed in more detail in chapter 2.5. Reducing the waste in the value chain activities and linkages among them is a way of gaining operational excellence. Searching and waiting for data, data translation, working with wrong data and reinvention of existing knowledge are common problems in the value chain. (Ameri and Dutta 2005.)

2.2.2 External forces

Manufacturers no longer rely solely on domestic resources as the costs have increased. Partners, who can economically provide the materials, components, and services needed, are sought worldwide. The collaboration of globally dispersed development teams has also become a common practice in most companies. As knowledge might not be located in a single source, knowledge management becomes more difficult in dispersed environments. Design teams might even be short-lived and dissolve once the design phase comes to an end. (Ameri and Dutta 2005.)

As the customers have a wide range of needs, the products are becoming increasingly complex. Systematic approach for preserving the integrity of complex product data is a major challenge. These products are more susceptible to engineering changes and there is more discrepancy between the as-designed, as-built, as-installed and as-maintained versions. When designing complex products, the decision making process relies highly on the availability of reuse of existing knowledge. (Ameri and Dutta 2005.)

Companies innovate and introduce new products at a high rate as customers' needs change rapidly. As the product life becomes shorter, a long product development process leads to products outdating rapidly. The need for shortening the product development process is one of the main reasons for implementing a PLM system. A collaborative environment with open sources of knowledge helps to speed up the product realization process and decision making. Such environment also enables concurrent performance of operations, which reduces time to market of a product.

According to Ameri and Dutta (2005), major phases of the product lifecycle have been characterized by extensive outsourcing since the early 1990's. For example, the awareness of the importance of early involvement of suppliers in the design process has increased. In order to integrate suppliers in the design process, knowledge dissemination in a functional manner is a fundamental requirement.

Finally, Ameri and Dutta (2005) discuss the environmental impacts products have at present. There are increased regulations which force companies to identify, evaluate and minimize the environmental effects of their products. Manufacturing companies need to take responsibility of the retirement of their products once they become obsolete.

2.2.3 Summary

The many definitions of PLM present similar objectives. In general, the target is to improve the activities in all the lifecycle phases and the linkages between the activities. This leads to faster product development and more efficiency in the whole lifecycle.

Reasons behind the PLM concept can be summarized to include the following objectives: excellence in value chain activities and in the linkages between them; efficient knowledge management and dissemination in globally scattered development teams and extended enterprise; innovative environment enabling creative and collaborative work methods; speeding up the realization process of complex products; customization of products based on complex customer desires and increased intimacy with the customers; lead-time reduction, prototype cost reduction, increase in reuse of components and reduction in late product changes.

2.3. Product lifecycle

Product lifecycle comprises the whole life of a product, from early conceptualization to retirement. In this context, the lifecycle is divided into three distinct phases: beginning of life (BOL), middle of life (MOL) and end of life (EOL). These are not to be confused with the four product lifecycle stages in sales and marketing: introduction, growth, maturity and decline. The previous four all belong to the middle of life stage.

There are also other definitions of the product lifecycle, such as the product lifecycle chain summarized by Silcher et al. (2010). This chain includes six phases: concept, design and development, production planning, production, maintain and support, and retire and disposal. Compared to the threefold model, the first three are included in the BOL stage, the next two in MOL and the last phase in EOL.

The lifecycle activities are summarized in the table below. They are split up into three groups: BOL, MOL and EOL.

Table 2.1. *Product lifecycle activities*

BOL	MOL	EOL
- Design and development	- Distribution	- Retirement
- Identifying requirements	- Use	- Disposal or recall
- Defining reference concepts	- Repair and maintenance	
- Developing prototypes	- Support	
- Performing tests		
- Production planning		
- Production		

These three phases and the connections between them are described in more detail in the following chapters. Furthermore, a lifecycle related business approach called Closed-loop PLM is introduced.

2.3.1 Beginning of life

The first product lifecycle phase, beginning of life, includes for example the following activities: identifying requirements, defining reference concepts, developing prototypes and performing tests (Terzi et al. 2010). In this phase, the product concept is generated and physically realised. The product design data created and managed efficiently must be distributed at the right time in the right context to ensure efficient manufacturing (Terzi et al. 2010). Engineers and designers need feedback information from distributors, maintenance and service engineers and customers on product status, field data of product usage and conditions of retirement of products (Jun et al. 2007; Terzi et al. 2010).

Field data from MOL could include maintenance event data, failure information, technical customer support information and updated bills of materials (BOMs). Data from EOL could include for example product, part or component lifetime information, recycle and reuse rates of each component, dismantling information and environmental effects information. (Jun et al. 2007.) The information is gathered in order to improve the product design and to make for example production systems, warehouse management and production logistics more efficient.

Beginning of the lifecycle is the area most focused on in the currently marketed PLM systems and tools. This lifecycle phase is the most convenient to manage and control as it comprises only the data, information and knowledge creation within the company. With the currently dominant PLM strategies, product data management becomes more difficult immediately after the product is delivered to the customer. For this reason for example a concept of closed-loop PLM has been introduced and conceptualized. This concept is briefly presented in chapter 2.3.4.

2.3.2 Middle of life

After BOL, in the middle of life phase products are distributed, used, repaired and maintained by customers or service providers. This phase includes distribution, use, maintenance and support, in other words the ‘real life’ of the product. The product is in the hands of its user or consumer, or service providers such as maintenance actors or service providers. As discussed by Jun et al. (2007), MOL actors benefit from BOM data, information for maintenance and service and product order information from the BOL phase. Also recycling and reuse information of parts and components can be obtained from the EOL phase. Based on the collected information, for example logistics optimization and predictive maintenance work can be performed.

Terzi et al. (2010) argue that for the most of the consumer electronics products in the market, the information flow breaks down after the product has been delivered to the customer. If the flow does not break, information like usage conditions, failures and maintenance can be used for creating reports about the status of products. The actors involved in other lifecycle phases have to make their decisions based on inaccurate and incomplete product information, if it is not collected during MOL phase. (Terzi et al. 2010.)

2.3.3 End of life

The third and final phase, end of life, starts from the time when the product does not satisfy the users anymore and is retired. It can be either disposed or recollected in the company’s hands for recycling. This phase includes for example the following activities: product collection, disassembly, refurbishment, recycle, reassembly, reuse and disposal. Knowledge related to product status, product content and material reuse should be passed to recyclers and reusers. (Terzi et al. 2010)

The final lifecycle phase benefits from the information concerning product waste stream management and product recovery decision making. Disassembly and assembly for remanufacturing information from BOL and usage status information, updated BOMs and maintenance history from MOL help in decision making in the EOL phase. (Jun et al. 2007.)

2.3.4 Closed-loop product lifecycle management

Closed-loop PLM is defined by Jun et al. (2007) to be a strategic business approach for the management of product lifecycle activities by using data, information and knowledge collected in the product lifecycle loop with the support of product embedded information devices (PEIDs) in addition to the traditional product data and knowledge management (PDKM) systems. A PEID is for example a radio frequency identification (RFID) technology based device, which gathers the whole lifecycle data of the product it is attached to. This data can be collected at any time and at any place, making the whole product lifecycle visible and controllable.

Depending on the product type, the type of PEID could vary from a simple RFID sensor tag to an embedded computer. It should have data gathering, processing and storing functions (Jun et al. 2007). The data collected could be for example mechanical, thermal, electrical, magnetic, radiant or any other measurable type of information related to the status of the product in its environment. The PEID should have a short range communication function in order to transfer the data collected to a PEID reader for example during a maintenance visit. The PEID reader should then have long range communication technology, for example a wireless internet connection, in order to connect to for instance maintenance data stored in a remote PDM database.

A proper PDKM system, along with a decision support system, would provide suitable advice for the closed-loop PLM actors at any time. Jun et al. (2007) state that developing the software between different applications can be considered to be the most demanding task and most challenging research area in the closed-loop PLM.

2.4. ICT systems for PLM

Information and communications technology tools, platforms and systems are a crucial part of PLM. At the moment, most of the tools are used in the BOL phase to support the various design and development activities. However, according to Terzi et al. (2010), the relevancy of ICT in MOL and EOL phases is increasing as the customer needs and the latest technology are taking effect.

In this chapter, three important subsystems of PLM are introduced: Engineering data management (EDM), Product data management (PDM) and Enterprise resource planning (ERP). Depending on the overall ICT architecture design, integration and implementation, the functionalities of the systems and tools might overlap. This could make some of the functions redundant, or create problems if a certain task has to be performed for each system separately. This results in unnecessary work being done and creates a risk of data quality deterioration.

2.4.1 Engineering data management

CAD applications and digital planning tools for a production planning process need a connecting layer between them. This collaborative environment referred to as Team Data Management (TDM) works very close to the CAD system. They support concurrent engineering in design teams. In the production planning part, the equivalent system is a so-called PPR database, which handles and integrates the product, process and resource data created in Computer-aided Planning (CAP) systems. Between these two systems, TDM and PPR, operates the Engineering Data Management system. EDM functions as an enterprise-wide archival and data management system. (Burr et al 2004) This definition is very close to what PDM is referred to as. The terminology is nebulous and multiple concepts fall under each name. Burr et al. (2004) include the TDM and

PPR system environments as a part between the CAE tools and EDM, which means they add a fifth element to the aforementioned CAE, EDM, PDM and ERP system landscape. In this study, the collaborative environment is referred to as EDM.

2.4.2 Product data management

Burr et al. (2003) use EDM as the collective term for engineering management, product management and product lifecycle management. A more recent definition (PLM Interest Group, 2012) argues that "PDM is the IT Platform for PLM", and from the opposite viewpoint "PLM is business context in which PDM is implemented". They therefore argue that "the terms 'PLM System' and 'PDM System' mean the same thing, and are interchangeable."

In the companies within this project, the term EDM is considered to be more of a concurrent engineering platform, in which all unfinished design objects and assemblies are stored during the product development. PDM system is considered to be the repository to which the versions released for production are transferred to. If there are separate EDM and PDM systems in use, the integration between them usually establishes a two-way connection, which means the finished objects can later be transferred back to EDM for further development.

2.4.3 Enterprise resource planning

Since the 1970's, material requirements planning (MRP), manufacturing resource planning (MRPII) and capacity requirement planning (CRP) software have developed into larger ERP tools that integrate and support activities such as financing, accounting and inventory management (Terzi et al. 2010). The tools included in modern ERP systems include supply chain management, customer relationship management (CRM) and advanced planning systems (APS) for managing and improving supplier and customer relationships and improving production scheduling (Terzi et al. 2010).

Enterprise resource planning (ERP) systems are bringing more and more influence on the product development process (Burr et al. 2005), thus mutually benefiting from integration to the other systems within the company IT architecture. ERP is utilized to support repetitive tasks typical of manufacturing and operations stages. PDM is instead used to support recursive and interactive activities that are usually not transactional. Thus both of them have their place in PLM as both work with product data and generate product data. For example the BOM is required by MRP and for instance product delivery dates are created. (Terzi et al. 2010.)

In the seven case studies by Sumner (1999), several reasons for implementing an Enterprise resource planning system were found. The business justification of an implementation project is usually linked to the reduction of operational level information systems and in operational excellence, for example cutting the costs of order processing and inventory management. Other reasons arisen in the study are staff reduction, data integration, standardization, access to timely and complete information, globalization and improving the reliability of customer service. (Sumner 1999.) Most of these latter reasons are valid also for the implementation of PLM systems.

2.5. Requirements for PLM

In order to improve the efficiency of interdisciplinary mechatronics product design Abramovici & Bellalouna (2009) argue that new management approaches and integration tools are indispensable. The solution has to be driven by the requirements of the mechatronic product design processes instead of IT considerations. Methods, processes and legacy tools have to be usable with minimal alterations within the new integration. Also the new implemented processes and tools have to be modular, follow standards and be reusable. The new integration should also have the flexibility to help in reacting to changes in the market, organization structure, processes, product and tools. Data, processes and software should be aggregated to reduce the complexity of the system. The new system architecture should also support concurrent development and communication between the experts (Abramovici & Bellalouna 2009).

Sharing some of the previous points of view, Lee et al. (2009) have introduced an architecture model for a ubiquitous product life cycle support system (UPLS). The requirements for the model could also be considered as a comprehensive list for the requirements of the PLM in general. Lee et al. (2009) have categorized them into functional level and data-level requirements.

2.5.1 Functional requirements

A great deal of structured and unstructured data is created, updated, transferred, removed, reused and stored in several application systems and stakeholders within the extended enterprise. To handle the unorganized data, Lee et al. (2009) define five functional requirements for the PLM architecture. The requirements are real-time data acquisition, closed-loop information flow, interoperability between devices and application systems, integration with existing systems and services and collaborative environment (Lee et al. 2009).

Real-time data acquisition means that in any lifecycle stage a user of the PLM systems should be able to collect the required product data and context data related to the product in real time. (Lee et al. 2009.) This would lead to reduced time consumption in almost every stage of the PLC, as all the information would be included in the product data and would be visible for the ones who need it.

Closed-loop information flow means that information transfers bi-directionally and transparently between every stakeholder involved in all three lifecycle stages, namely BOL, MOL and EOL (Lee et al. 2009). To achieve such a situation, it is crucial that all the product information and data is documented as well as possible in every step of the lifecycle.

Interoperability between devices and application systems is important in order to guarantee that the numerous software and hardware elements in different life cycle stages communicate with each other seamlessly (Lee et al. 2009). Mostefai et al. (2005) define interoperability as methods to organize, store, access, convert and exchange data correctly and seamlessly. The system architecture must be designed and maintained in a way which supports seamless data exchange and at its best no data quality deterioration occurs. As the PLM includes all phases in the product lifecycle, the exchange of data and information between different phases and stakeholders becomes a critical element of PLM (Terzi et al. 2010).

Integration with existing systems and services is important when modifying the architecture. The information technology landscape of an enterprise usually consists of several applications and tools such as CAx, ERP, EDM and PDM. When the architecture is modified, it is important to reuse the existing functions comprehensively and remove all redundant functions. (Lee et al. 2009) CAx is an umbrella term for Computer-aided Technologies and includes all the Computer-aided Engineering (CAE) tools and systems.

Collaborative environment should be in operation throughout the entire product life cycle. Currently collaboration is focused on the BOL stage, but PLM should support transparent information exchange and feedback between all the participants also at the MOL and EOL. (Lee et al. 2009). Ameri & Dutta (2005) also argue that to ensure effective communication, both the upstream and the downstream flow of information between customers and manufacturer should be as seamless and direct as possible.

2.5.2 Data level requirements

The data gathered and created during the life cycle of the product includes not only the product data itself, but also product-related data such as the business, maintenance and expiration data generated during MOL and EOL. For a seamless flow between the PLC stages the data-level interface is the key. Lee et al. (2009) identify four data-level requirements for a functioning architecture: use of standardized data, data interoperability, traceability of individual product information and data encryption and user authentication.

Use of standardized data is required for a seamless information flow in the course of the entire lifecycle (Lee et al. 2009). For example the Standard for the Exchange of Product Model Data (STEP) is an international standard produced by International Standards Organization (ISO) for all aspects of technical product data (STEP Tools, Inc. 2011).

Data interoperability between the existing data models used by various stakeholders should be carried out with the standardized data. Enforcing the same data model on every stakeholder is impossible. (Lee et al. 2009.)

Traceability and management of information of individual products means that it is a requirement to be able to individually trace every product produced. Stakeholders should be able to access the information related to a product and its main components at any other stage of the product lifecycle. (Lee et al. 2009).

Data encryption and user authentication is required as there are several stakeholders involved. The amount of information is enormous and it should be accessible in a limited fashion. The model Lee et al. (2009) are developing is designed to be able to manage access authentication for various information. The system should also control the certification of users requesting the information through various application systems.

2.6. PLM maturity model

This chapter will summarize the maturity model chapter introduced by Stark in his 2004 book Product Lifecycle Management. The focus of this summary will be on the PDM architecture related elements, rather than company strategy or product development related shortcomings, which are also addressed in Stark's study. In his evolution model, Stark also introduces a five-step process and these steps will be defined for each of the four stages. For comparison, another maturity model by Batenburg et al. (2005) is briefly introduced in chapter 2.6.5.

The five step process for each step in the model by Stark is the following: understand the current (as-is) situation, understand the desired future (to-be) situation, select a strategy to go from as-is to to-be, develop detailed plans to correspond to the strategy and implement the plans (Stark 2004). In this chapter the focus will be on current and future situations, rather than strategies linking them. The as-is and to-be situations will be studied concerning the PDM environment and usage within the company and its extended enterprise. In general, most of the to-be goals of one stage are the as-is situation of the following stage. Strategies and corresponding plans for the implementation will be briefly introduced.

2.6.1 Stage 1: Traditional

According to Stark (2004), companies in the traditional stage, or the first stage of evolution, do not realize the value of product data and do not think of a product having a lifecycle. These companies are using computer systems, such as CAD, to automate previously manual tasks, but these engineering tools have little or no interoperability. All the product data is stored in stand-alone databases. As the stage of PDM is still in its infancy, these companies have little interaction or exchange of information with their customers.

For a company in the traditional stage, there are several ways to move forward to a desired to-be situation. At a ten-year horizon, a company could have for example the following objectives. They should have an enterprise-wide PDM system, which would also stretch to the extended enterprise. Also the applications within PDM could be integrated and the PDM system could be integrated to other major systems, such as CAD or ERP.

To achieve the to-be situation, Stark (2004) gives as examples five potential approaches: Stand-alone, Step-by-step, Reengineering, Balanced and Big Bang. Briefly described, the Stand-alone approach is to start the implementation of PDM in a small part of the company instead of drawing every part to join the project. Step-by-step is to incrementally move forward to the desired situation in a clearly-understood manner. The gains of this approach might never add up to a significant benefit, due to many small steps. Stark (2004) gives the following steps concerning PDM as examples: installation of a PDM system, identifying data to be managed, cleaning the data, loading meta-data, classifying parts, establishing a data vault and implement check-in/check-out. Reengineering focuses management attention more on making changes to processes than on other components, for example those related to PDM. In a Balanced approach all the components are addressed to at the same time, which requires plenty of up-front work to understand how to move forward. A Big Bang aims to implement all the changes at the same time. The advantage is that as everything is implemented at the same time, great improvement can be made quickly, but failing in the project will quickly lead to a disaster.

Stark (2004) states that the key for moving forward from the traditional stage is to focus on change implementation in general, as poor reaction to change is usually the thing what keeps the company in the first level of the maturity model. Major change projects require adjustments to the company culture and behaviour. Most of the approaches require quick change, which is why Stark (2004) recommends the Step-by-step option for a company in the traditional stage.

2.6.2 Stage 2: Awakening

A company in the second stage has moved forward in several ways. There is recognition of the need for change and some people, although a minority, are already changing their attitude. Many actions toward the to-be situation of the previous stage have been started, but are still uncoordinated and often contradict each other. Stage two companies have realistic views of the situation, understanding of the difficulties ahead and know their limits. They typically define the expected to-be situation in a short or medium term, rather than at a ten-year horizon.

The as-is situation in the awakening stage has improved from the first stage, but is still quite deficient. Few people understand the PDM yet. From the PDM viewpoint, the company still doesn’t have electronic interaction with its customers or even between its departments. Product data is stored in stand-alone vaults and other databases separately in each department. They might have integrated some engineering computer systems and use separate PDM applications for activities such as quality document management or management of operating procedures.

For a company on this stage, the short or medium term goals could include some of the following: There should be a company-wide PDM approach and understanding of the value of product data. Data should be stored in a cross-functional electronic vault and shared more with customers and partners. Product data should be exchanged electronically between departments. At this stage several PDM applications are in use, but not all of them are integrated yet. There might be a simple level of integration between

PDM and some other computer systems such as ERP already. These goals help move forward to the third stage: adapting.

2.6.3 Stage 3: Adapting

Improvements to the previous stage are again noticeable in technical aspects and also in the company culture. The company is now able to share data with customers and partners and a cross-functional electronic vault for data storage. This means that some of the implemented PDM tools are integrated and there might be, for example, a simple integration between PDM and ERP. There is an overall understanding of the value of product data and a company-wide PDM approach is taking shape.

Company on the third stage will know its capabilities and have a good understanding of where it is and where it wants to be. People have more confidence in change projects and have become used to change. There is a desire to overcome the past error of starting uncoordinated and even contradictory change actions to make more progress rapidly.

The next steps to reach the fourth and final stage of this model include some or all of the following PDM projects. PDM functionality should be extended to the customers and suppliers, or the extended enterprise. In addition, integration of PDM with other computer systems needs to be extended. The entire workflow of the product development process should be automated. All data and documents related to the process have to be managed by PDM and in order to maintain security and control, the ownership of all the data has to be clear. This requires that all users have to be properly trained to use the PDM functionalities they need.

2.6.4 Stage 4: Modern

When reaching the fourth stage, a company has all the essentials for effective PDM in place. There is an enterprise-wide PDM system and a widespread understanding of PDM and PLM. The product data is primarily in electronic format and there is an organization for managing it. The PDM applications are fully integrated and there is a widespread integration between PDM and related systems, for example CAD or ERP. Most engineering computer systems are also integrated. There is regular electronic integration and exchange of product data and documents between departments, customers and suppliers.

A company in the modern stage, or the fourth stage, will have moved forward from the previous stage in several ways. There will be a common goal for the company, effective processes in use, product data and information is in control and managed in efficient computer systems. Also the people involved know their role and understand the need for change. It will take a very long time to reach the fourth stage, but it is not a final level as there are still several ways to improve the situation.

As the PDM system is more developed, the amount of information managed by it can be increased. One project could be to ensure that all data and documents related to the product development process are managed by PDM. Everyday tasks could be developed for example by increasing the flow of information, reducing access time to information and enabling better use and reuse of information. One goal should be to integrate PDM into PLM as well as to maintain total integration of PDM with other computer systems. The company could help its suppliers and customers with implementing their own PDM systems. They also need to ensure all users continue to be trained to use the PDM functionality they need.

2.6.5 Alternative maturity model

This chapter will present another maturity model for comparison and compare it to the one by Stark (2004). This concept by Batenburg et al. (2005) is also divided into four levels, from zero to three: no investment (0), departmental level (1), organizational level (2) and inter-organizational level (3). These levels are more non-specific than the ones defined by Stark (2004) and mostly discuss the matter of how the PLM systems are spanning across the organization. Batenburg et al. (2005) address the need to determine the desired maturity level of the company. Given the nature of the maturity concept, they emphasize that it is too ambitious to increase more than one maturity level at once.

The level zero presents a situation where there is no PLM investment, or it is on 'ad-hoc' basis only (Batenburg et al. 2005). Ad-hoc is a situation where a certain system or tool is implemented to work only for a specific problem or task and is not intended to be used for other purposes. On this level there is no one responsible for PLM and there is no vision for PLM in general (Batenburg et al. 2005). Without a responsible party, there cannot be consistent PLM processes and supporting systems. This leads to product information scattering throughout the organization, which hinders strategic decision-making. (Batenburg et al. 2005.)

On the first level, or departmental level, there is a 'silo' orientation. This means that PLM is seen as a data management problem that should be dealt with on departmental level. Therefore there is no overall vision to coordinate the local initiatives. Often the development or engineering departments are the first to implement PLM systems. At this level, all the information regarding the early stages of the lifecycle is stored in a central system. (Batenburg et al. 2005.)

A company on level two considers PLM as a business problem that requires a corporate vision and an integral approach. This stage is referred to as the organizational or cross-departmental level. In addition to engineering and development using PLM processes and systems, other departments are heavily involved on the second maturity level as well. The processes involved in PLM are defined in a way that makes use of PLM systems being implemented across departmental borders for company-wide support. Also, other major enterprise systems, such as ERP, are integrated with PLM. All the product information is stored in a single central system and there is also control information available regarding the PLM processes. (Batenburg et al. 2005.)

On the inter-organizational level, the third and final maturity level, PLM is finally seen as a business problem spanning the entire product lifecycle. This means that the systems are also operating outside the company, involving the entire supply chain. This requires that the supply chain is taken into account already when defining the PLM vision. The processes are defined in a way which takes advantage of the PLM systems being integrated across the organizational borders with suppliers. Thus collaboration within the supply chain is made possible throughout the product lifecycle. All the product information across the lifecycle is stored in a central system. Therefore the lifecycle is transparent and enables proper decision-making concerning the development of the product. (Batenburg et al. 2005.)

The definitions of the last two levels of the maturity model imply that a single source for all the product data would be an ideal solution, which might not always be the case, at least for the time being. The various arguments in favour of and against a single source architecture type are discussed in chapter 3.5.

2.6.6 Summary

In the maturity model by Stark (2004), focus is on several aspects of an organization, people and technology. This chapter focused on the parts concerning PDM and technical and architectural aspects. Stark defines the four stages of evolution by listing details of the as-is situation, to-be situation and activities leading to the to-be situation. All the stages were presented regarding the above details. The stages are not definite, so a company might have achieved development steps introduced in more than one stage. The latter model by Batenburg et al. (2005) concentrates on how the PLM systems are implemented within the organization and the supply chain.

For the purpose of this thesis, a four level PLM maturity model is put together based on the two models presented in this chapter. For each of the levels from A to D, this figure includes a description of the application of PLM, extent of the users and organizations involved in the PLM application, level of integration, level of interoperability and finally a summary of the situation as a whole. The created model is presented in the table 2.2. below.

***Table 2.2.** PLM maturity level summary*

	Level A	Level B	Level C	Level D
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	Company-wide understanding of the importance of product data is taking shape	PLM is seen as a business problem spanning the whole product lifecycle
Involvement and understanding	From few to no people involved	Few people understand PLM	It is clear for everyone where the company is and where it wants to be	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple departmental integrations between some PDM tools	Integration between PDM tools and simple integrations with for example ERP	PDM tools are fully integrated and there is widespread integration with related systems such as ERP
Level of interoperability	Between individual tools only	On a departmental level	On a cross-departmental level	Across the extended enterprise
General description	There is no PLM investment and individual legacy systems are used.	PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.	PLM is understood relatively well and integrated on a cross-departmental level	PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.

The table ranges from level A to D. A is seen as the initial level where PLM is not thoroughly understood and investments in it have not been made. D is the sophisticated level where PLM activities function across the extended enterprise and throughout the lifecycle of a product.

3. PLM ARCHITECTURE

3.1. Overview

In this chapter, two theoretical models of PLM architecture are introduced. Both models have several different approaches. Based on these two models and further studies, three prominent architecture designs and their implementations will be discussed in chapter 3.4. The integration of processes and products within a PDM system has proven difficult to achieve in the industry. This can be seen in the integration of different engineering disciplines, such as the software and mechanical engineering disciplines, which have been allowed to evolve separately (Bergsjö et al. 2008).

According to Seger and Stoddard (1993), as cited by Pienimäki (2005), information technology architecture describes information technology infrastructure and includes procedures and instructions on how to organize information technology resources. Furthermore, according to Cook (1996), as cited by Kilpeläinen (2006), the use of architectural descriptions reduces the complexity of information systems and reveals the redundancy and overlap in business processes. Architectural descriptions also provide a tool with which better bring forth the organizational strategic objectives in practice (Kilpeläinen 2006).

Reasons for system integration are found on many levels. Firstly, integration improvements can benefit in certain process steps within design and production planning. More important and potential is the optimization of the interfaces between different process stages. This means for example transfer of data between departments. All information exchange tends to lead to a loss of knowledge, which can be reduced by properly integrating the processes. Burr et al. state that “information quality and, as a result, product quality profit greatly from the reduction in loss of knowledge at the process interfaces”. Several of the systems on the market offer similar functionalities for certain applications, thus creating inconsistencies and redundancies. (Burr et al. 2004) By integrating all the applications and thus enabling the exchange of data between them, several benefits are achieved. The product development time shortens due to collaboration, the data exchange is automated and thus faster and redundant data management is reduced. All of these advantages reduce the overall costs and lead to a faster product development, increased quality and a shorter time-to-market. (Silcher et al. 2010.)

The vast amount of functionality will not benefit the company, unless the gaps between the systems are bridged systematically (Burr et al. 2004). Every software system, such as CAD and CAM, is used for a certain part of the lifecycle process, for example design or manufacturing. These systems are independent and usually their information models are not compatible with each other (Cui et al. 2006). In some areas the integrations have been developed to a mature level already over twenty years ago. For example the co-operation between CAD and FEM tools is an excellent example of smooth interoperability (Andersson et al. 1999, as cited in Burr et al. 2004).

Abramovici and Sieg (2002) state that collaboration and dynamic integration of all the business partners across the value chain are tremendous trends for successful utilization of PLM systems. Based on the findings of this research, at present the system integration throughout the supply chain still seems to be a challenge. Abramovici and Sieg (2002) argue that the next generation of PLM systems will be more standardized and will allow an easier system implementation by configuring templates for different industries or user types. These turn-key systems are predicted to be more appropriate for small and medium enterprises and are expected to form a significant potential for the PLM market with increasing revenues for licences and services. They also mention that leading vendors have started to downgrade their systems to be faster to implement and easier to use. The case companies in this research are all large enterprises and the PLM implementation projects seem to take time and resources. The amount of legacy solutions makes changing to a turn-key system a very complex project.

3.2. Integration possibilities

Crnkovic et al. identify three levels of integration in their 2003 book “Implementing and Integrating Product Data Management and Software Configuration Management”. Even though they concentrate on the integration of PDM and SCM, the same logic can also be applied to the integration of other engineering tools and subsystems like PDM and ERP or EDM and PDM. All of these applications and systems are referred as tools in this chapter. The levels are full integration, loose integration and no integration.

In full integration a homogenous system containing all the subsystems with a common repository and common information model is built. Loose integration means that the each system has its own functions and local data storage. The systems are independent, but there are mechanisms for information exchange and thus data can be accessed from both systems. If there is no integration, the data transfer between the systems has to be done manually by users.

3.2.1 Full integration

Crnkovic et al. (2003) define full integration as a package with all functions using common structures, data, user interfaces and application programming interfaces (APIs). The structure of the integration model is based on layered architecture. The lowest layer or tier is the data repository layer, which includes databases, file systems and information models. An information model is a logical organization of objects, their constraints and the relationships between them (Crnkovic et al. 2003, pp32). The middle layer, or the business layer, consists of different tools and services to support the business logic. All the tools have a standardized API for connection to the information models in the repository layer. Using a similar standardized API, the business layer is connected to the user interface layer. The upper layer's function is human application interaction, which is as independent as possible of any particular tools due to uniformity achieved by using the latest technologies. This means for example web-based technologies, which force the user to enter the data in a desired way.

A single database for all the data is superior in terms of data quality. Deterioration of data through the exchange between systems is minimal and the amount of duplicate files which might or might not be in synchronization with each other is virtually non-existent. Problems with the full integration occur when implementing the model into real life. The tools available on market usually have their own specific API, which does not necessarily match the functionality of the tool completely. The integration between a middle layer tool and the repository layer is very tight, which makes it very difficult to create a common repository for all the repositories of the tools. Tools have similar types of repositories, but there isn't a common information model required for integration. The lack of a standardized information model is the main challenge in the full integration model. This can be solved by using tools from only one system supplier, but the possibilities on the market are limited and usually lack some required functionalities. PLM implementation is rarely, if ever, carried out with a complete abandonment of the previous tools. Other problems of relying to a single vendor are discussed in chapters 3.4.2 and 3.5. (Crnkovic et al. 2003.)

3.2.2 Loose integration

When the different tools operate more independently of each other and store data in their own repositories, the integration can be defined as loose. The information models in the repositories are different and can only be accessed from a particular tool. Information exchange between the tools is carried out by additional interoperability functions. These functions can be separate applications or integrated within the tools. (Crnkovic et al. 2003)

The main advantage of this approach is that it doesn't require a common information model. This enables the use of tools from various vendors. On the other hand, the lack of a common information model leads to the requirement for interoperability functions between the tools. The development of these functions can be difficult and might also require changes in the existing functions. Crnkovic et al. adress the problem: which should be responsible for developing these functions, the software vendors or the customers themselves. As data is stored in repositories of each tool, it is possible that the same information is stored in several places. Thus there is a risk that the data is updated in only one of the repositories and becomes inconsistent. The tools might not be compatible in both directions, for instance if changes in one are synchronized to the other, the reverse might not be possible. (Crnkovic et al. 2003.)

To ease the interoperability functions, there are mechanisms that provide support for many standard functions. These mechanisms are referred to as middleware, which works as the middle layer in PLM integration and extends to multiple tools. The architecture model for a ubiquitous product life cycle support system by Lee et al. (2009) introduced earlier in chapter 2.5 is an example of middleware.

The integrated architecture can concentrate on a single master tool, for instance PDM. In this case, the communication between the user and the tools should be carried out only via PDM. This master system is responsible for updating the other tools and thus provides control of the consistency of duplicated data. (Crnkovic et al. 2003.)

3.2.3 No integration

In case there is no integration between the tools, all the data transfers between them have to be done manually. This naturally leads to a great risk of inconsistencies in the data due to human error and the lack of standardization in information models. The data update routines, such as import and export functions, have to be well defined and strict in order to avoid inconsistency. (Crnkovic et al. 2003.)

3.2.4 Summary

In this chapter three levels of integration were identified: full integration, loose integration and no integration. Full integration is a model in which a homogeneous system contains all the subsystems used and includes a common repository and a common information model for all the product lifecycle data. It is based on layers, which jointly connect the actions of the users of different tools to the product data in the database. Its main advantage is that the data is stored in only one database and all the tools intercommunicate with the same information model. The desire for a common information model is however very difficult to achieve, when implementing the full integration model into real life. This is because of the lack of standardization among the tools. PLM bundles by individual suppliers do have their common information models, but are still somewhat immature and lack some required functionalities.

In the loose integration model the need of a common information model is bypassed by using dedicated databases for individual tools. Information model heterogeneity allows the use of tools developed by various suppliers. To enable the data and information exchange between various tools, loose integration requires interoperability functions. These functions can be difficult to develop and require updating if one of the tools is updated in a way which modifies the information model it uses.

If there is no integration, the data is divided into several databases, but there are no interoperability functions. This means all the data exchange between the tools has to be done manually, which leads to a probable risk of data quality deterioration. This is usually the “as is” state when a PLM implementation project is launched.

3.3. Alternative integration architecture approaches

This chapter will introduce another integration architecture model which shares some aspects with the one by Crnkovic et al. The models will be compared with each other in chapter 3.5. In their study, Bergsjö et al. (2006) identify four different approaches as ways to connect the tools used for product development. Similarly to Crnkovic et al. (2003), Bergsjö et al. focus on PDM and SCM integration concepts in order to simplify the analysis. The four approaches are best-in-class, one system as integrator, all-in-one integration and peer-to-peer integration.

According to Bergsjö et al. (2006) there are several things that should be considered by a company planning to modify its system architecture. He addresses the following questions: To what extent can a single PLM supplier be relied on? Is it acceptable to have less functionality in the applications in order to have more integrated system architecture? Will there be major changes to systems in the future? Should tools and systems be customized to fit the process, or vice versa? Is integration necessary with all disciplines, or is it possible to work with subsystems?

3.3.1 Best-in-class

The best-in-class integration approach takes place on two levels. The levels are analogous to the layers defined by Crnkovic et al. (2003). The first integration level is between engineering tools and applications and a development discipline specific subsystem, such as PDM or SCM. The other level is between the sub-system and the enterprise PLM system.

Due to two levels, the implementation of standards will be more difficult to manage. The communication between the subsystem and PLM will most likely be carried out by a standard protocol, but the first level is more problematic. As the level consists of integration of several different tools and applications to a subsystem, the protocol between them is more likely to be software-specific. (Bergsjö et al. 2006.)

3.3.2 One system as integrator

In the second approach, the current PDM system is replaced by a direct integration from the engineering tools to the PLM system. The approach can be carried out using a PLM bundle with integrated CAD tools or by integrating the current tools to PLM directly instead of through PDM as in the best-in-class approach. The PLM system would then be customised to communicate and share information with the SCM system. In order to avoid any problems with data loss or information quality deterioration, the communication interface between the two has to be well designed similarly to the best-in-class approach. (Bergsjö et al. 2006.)

3.3.3 All-in-one integration

The third approach is to remove individual management systems and to integrate them into one supreme system. The approach is similar to a full integration introduced by Crnkovic et al. (2003), which was discussed earlier in chapter 3.2.1.

This integration approach has several problems. The development disciplines and their needs differ greatly, which creates vast requirements for the functionality and performance of such supreme system. Another problem is that implementing a new technology branch with new tools and applications that do not follow the standards required by the PLM system would be difficult to implement. When updating one of these tools, the PLM vendor has to be relied on to develop support for the latest versions. It is also difficult to find a PLM system which is able to handle the needs of mechanical and electrical engineers and all other stakeholders. A total reconfiguration of the current information model might take years to implement. One possibility to use this approach is to order a complete bundle from one PLM supplier if the limitations in functionality are not crucial. (Bergsjö et al. 2006)

3.3.4 Peer-to-peer integration

The last approach introduced by Bergsjö et al. (2006) involves peer-to-peer communication. The subsystems such as PDM and SCM are communicating on equal basis with each other. There is no such supreme system as in all the other approaches covered earlier in this chapter. According to Bergsjö et al. (2006), peer-to-peer integration could be related to a loose integration introduced by Crnkovic et al. (2003).

The main challenge of this approach is that it requires every program to communicate with every system it needs shares data with. In order to achieve this interoperability, several modifications to the programs or systems might be needed. Updates of parts of the architecture might cause a need to modify the communication interfaces of the other parts. On the other hand, the network traffic and the sizes of the databases are reduced. This is because the data is stored in development discipline specific databases and the intercommunication is done from peer to peer instead of transferring the data through a supreme system. Then again, the lack of an umbrella system to log activities makes control, supervision and error-detecting more difficult. With this integration approach there are endless possibilities to develop domain-specific information models, as long as the intercommunication between the systems is according to standards. (Bergsjö et al. 2006.)

3.3.5 Summary

The benefit of architecture integration can be approached for example from the viewpoints of user satisfaction and system manageability. Bergsjö et al. (2006) present the problem of whether it is better to have a company-integrated system or to differentiate the development of separate engineering disciplines. Engineers who use the tools require at least the amount of functionality they have had before, thus resisting any change which might hinder the usability of a software or system. This holds companies using legacy systems or customizing the new software implemented drastically. From the other viewpoint, the amount of different subsystems and tools can lead to a very difficult to manage architecture with several interoperability functions and integrations between every system. This trade off between support for management and engineering in relation to the degree of integration is demonstrated in Figure 3.1. below.

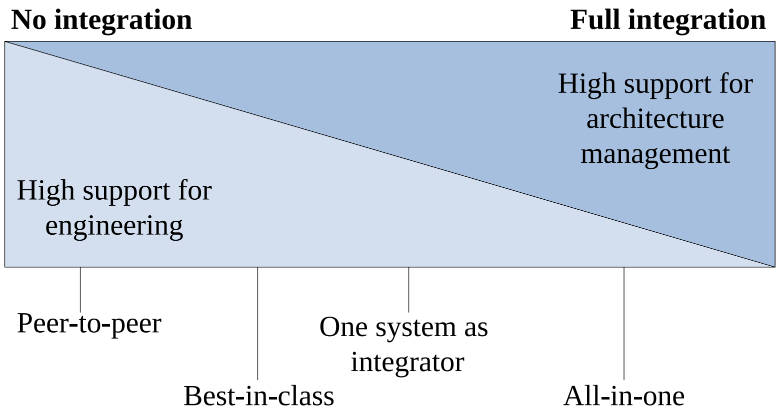

Figure 3.1. *Relation between the levels of integration and support (adapted from Bergsjö et al. 2006).*

The PLM bundles provided by the largest suppliers, where one system acts as an integrator, offer relatively high maturity, and are cost-effective because of the low need for modifications. But being committed to one integrator creates potential challenges, such as the lack of support for non-mechanical development disciplines. (Bergsjö et al. 2006)

Bergsjö et al. (2006) argue that the fully integrated, or all-in-one, solution is still quite immature. A supreme system with company-wide database, which would include tools and applications for every engineering discipline, has not yet been developed. All the tools are tightly integrated to the system, so it is practically impossible to choose a different tool to be used in parallel with the fully integrated solution.

According to Bergsjö et al. (2006), the loose, or peer-to-peer, integration has potential, but is not yet considered mature enough for a company with multiple tools that need to share data. The development of such middleware to manage the communication between the tools and databases is essential. In the journal paper by Lee et al. (2009) introduced earlier in chapter 2.5., the development of a framework for an architecture for ubiquitous product life cycle support system (UPLS) is discussed.

3.4. Architecture implementation

The two different architecture integration models presented by Crnkovic et al. (2003) and Bergsjö et al. (2006) can be put together as three major trends of integration: legacy architecture, single source architecture and service-oriented architecture. The linkage between the models is presented in the figure below.

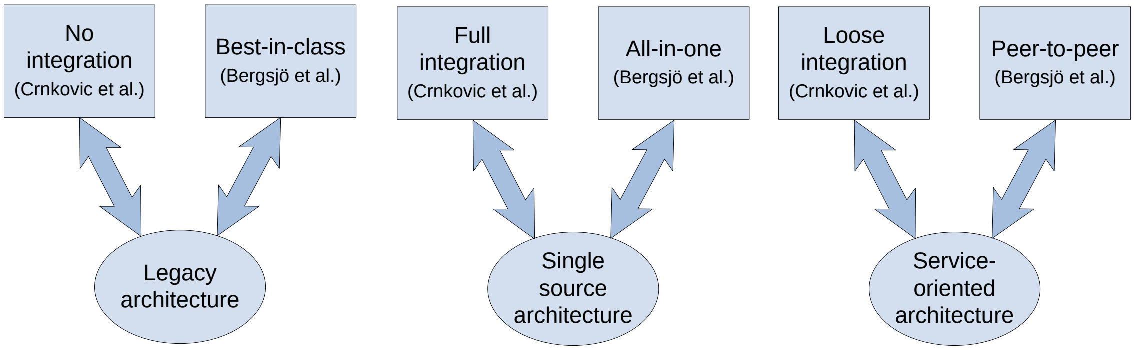

Figure 3.2. *Connections between the architecture definitions by Crnkovic et al. (2003) and Bergsjö et al. (2006).*

The figure illustrates which of the approaches are essentially describing the same architecture types. The fourth integration approach by Bergsjö et al. (2003), one system as integrator, is not included in the picture. This approach can be carried out using either a PLM bundle or by integrating tools to the overall PLM landscape through PDM as in the best-in-class approach.

3.4.1 Legacy architecture

The term legacy, or ad hoc, architecture can be used to define the state of the architecture of tools, applications and systems of a company before or in the starting point of a PLM software harmonization project. This means there is little or no integration between the subsystems and data exchange is performed mostly manually. The legacy system might have a unifying name, but in practice usually consists of many different databases and applications (Bergsjö et al. 2008) with limited or non-existent interoperability.

More information about this approach can be found in chapters 3.2.3. and 3.3.1. Architecture with no integration develops naturally when tools and applications are added to the company information technology landscape whenever a specific functionality is needed and without a long term strategy.

3.4.2 Single source architecture

The all-in-one integration introduced by Bergsjö et al. (2006) shares several aspects with full integration model defined by Crnkovic et al. (2003) and both form a single source architecture. Typical for a single source architecture and for the two integration models is that it is important that all the data is stored in a single database with which each separate tool communicates. As the master database usually belongs to one system, such as PDM or ERP, it can be defined as the PLM backbone.

Relying on a single PLM supplier for the whole IT architecture can be risky. Terzi et al. (2010) argue that there is no comprehensive and well-accepted commercial PLM tool yet available and there will not be one in the near future. Bergsjö et al. (2008) argue that for companies implementing PLM, it is important to realize the value of their current processes and business logic, which have probably been crucial for their entire business and uniqueness. This is why Bergsjö et al. (2008) do not believe that outsourcing the PLM system by implementing a commercial and easy to manage software is the best approach, as it is critical business value to control and maintain the PLM architecture, especially when there is a global extended enterprise involving suppliers in all lifecycle stages. The challenge is to keep the essence of the successful business logic of the past while implementing new tools required for the new PLM setup. This means that it is risky to outsource the way a company is doing business to an IT supplier, who does not necessarily understand the requirements of the particular field of business. (Bergsjö et al. 2008.)

3.4.3 Service-oriented architecture

The most discussed and studied architecture model at the moment is the Service-oriented architecture (SOA). Abramovici & Bellalouna (2009) state that there is no widely accepted uniform definition of the term service-oriented architecture and that some sources regard SOA as an IT architecture paradigm and some as a service-oriented restructuring of all business processes. In this study, service-oriented architecture is considered as an approach which integrates heterogeneous applications and databases. In this context, heterogeneous means that the information models and processes vary. Therefore SOA will make it possible to bridge gaps between for example PDM and SCM systems.

Reflecting to the models introduced earlier, SOA can be considered as a loose integration (Crnkovic et al. 2003) and as a peer-to-peer integration (Bergsjö et al. 2006). In these models the data is spread around several databases, which leads to a requirement for intercommunication between various tools. One benefit of SOA is the possibility to assemble the implemented services to complex workflows (Silcher et al. 2010). These assemblies are then available as new services. A service layer, or middleware, needs to be developed for this purpose. The middleware of SOA is an Enterprise Service Bus (ESB) which offers additional functionality, such as execution and administration of workflows (Silcher et al. 2010). This type of architecture implementation allows the use of legacy tools and applications. Keeping the old tools available, productivity will not decrease because of, for example, a lack of certain functionality in substitute design software. The middleware is the main challenge of this integration model, as it is very difficult to develop and maintain, as discussed earlier for example in chapter 3.3.5. Continuous governance is required for the SOA PLM system to work. Rules and a responsible organization need to be assigned in order to maintain the processes and IT environment (Bergsjö et al. 2008).

Because of the lack of standardization and common information models between the software of various suppliers, the task of creating the middleware needed for SOA is still very challenging. Competing suppliers have little reason or motivation to cooperate with each other to have standardized information models.

The usability benefit of a SOA is that engineers could continue to work with the legacy applications they are accustomed to, but at the same time get customized services for performing information management tasks. The information flow which has traditionally been based on people and on sending notifications to the right recipient would be replaced with more efficient information exchange, in other words using the interoperability functions provided by SOA. Bergsjö et al. (2008) conclude that SOA is an improvement to other PLM architectures as it allows transparency and flexibility in IT integration. Silcher et al. (2010) also state that compared to other architectures, the most important benefits of SOA are higher flexibility and interoperability.

3.5. Architecture model analysis

In this chapter each architecture type is evaluated by their strengths and weaknesses and compared by determining what improvements and deteriorations would be probable if switching from one architecture type to another. Tables 3.1. through 3.3. list the strengths and weaknesses of legacy architecture, single source architecture and service-oriented architecture.

Table 3.1. *The strengths and weaknesses of* ***a legacy architecture****.*

Strengths	Weaknesses
- No need for change, users can work with the sub-systems and processes they have used earlier - A sub-system can be replaced without effect on other sub-systems - "If it works, don't fix it", the old architecture is familiar for everyone	- Manual data exchange between the sub-systems is time-consuming and leads to loss of data or data quality deterioration - Complex management as there is a large amount of separate databases and the same data is represented in more than one database - Competitors might implement a more efficient PLM architecture, which leads to falling behind on development - Point-to-point integration leads to complex, inflexible, unsustainable and unreliable architecture with prohibitively high costs

Table 3.2. *The strengths and weaknesses of a* ***single source architecture****.*

Strengths	Weaknesses
- Using only one database ensures data correctness and simplifies security management - Tools used can reach all the data, as it is stored in a single location - Can be based on a single supplier - All product information across the product lifecycle is stored in a central system making the product lifecycle become transparent enabling proper decision-making concerning a product. (Batenburg et al. 2005) - A truly integrated controllable system where data is represented in only one place (Bergsjö et al. 2006)	- Requires either heavy customization of present sub-systems and processes or adaptation to new tools and processes. - Very difficult to extend or integrate with other applications (Silcher et al. 2010) - System replacement is expensive - Relying on a single PLM bundle supplier is risky - Hard to realize due to the distributed nature of engineering work (Bergsjö et al. 2008)

Table 3.3. *The strengths and weaknesses of a* ***service-oriented architecture****.*

Strengths	Weaknesses
- Higher flexibility and interoperability - No need for engineers and other users to learn to use new tools, because of the possibility to integrate legacy sub-systems - Not dependent on a single supplier - All tools co-exist with a robust web of databases (Bergsjö et al. 2006)	- Maintaining the integrations between different systems can be very difficult - Supervising and controlling the use is difficult - The web of databases is difficult to manage (Bergsjö et al. 2006) - In a worst-case scenario, updates or changes in one system affect all the other systems - Tools are difficult to replace, unless they are standardized - Every tool must be customized - Data errors are hard to find and correct

When going through the pros and cons of the three architecture implementation models, three sensible architectural evolution scenarios can be defined. These three scenarios are analysed regarding the opportunities and threats of changing from one architecture type to another in tables 3.4. through 3.6.

Table 3.4. *Scenario #1: List of opportunities and threats if a legacy architecture is replaced by a single source architecture.*

Opportunities	Threats
- Using only one database ensures data correctness and simplifies security management - Tools used can reach all the data, as it is stored in a single location - Can be based on a single supplier - All product information across the product lifecycle is stored in a central system making the product lifecycle become transparent enabling proper decision-making concerning a product. (Batenburg et al. 2005)	- A sub-system can no longer be replaced without effect on other sub-systems - Requires either heavy customization of present sub-systems and processes or adaptation to new tools and processes. - Very difficult to extend or integrate with other applications (Silcher et al. 2010) - System replacement is expensive - Relying on a single PLM bundle supplier is risky - Change resistance leads to leadership challenges - Need for major change, users can no longer work with the sub-systems and processes they have used earlier - Implementation project includes a risk of failure - Hard to realize due to distributed nature of engineering work (Bergsjö et al. 2008)

Table 3.5. *Scenario #2: List of opportunities and threats if a legacy architecture is replaced by a service-oriented architecture.*

Opportunities	Threats
- Higher flexibility and interoperability - No need for engineers and other users to learn to use new tools, because of the possibility to integrate legacy sub-systems - Enhanced collaboration possibilities - Faster product development time	- Maintaining the integrations between different systems can be very difficult - Tools are difficult to replace, unless they are standardized - Every tool must be customized

Table 3.6. *Scenario #3: List of opportunities and threats if a single source architecture is replaced by a service-oriented architecture.*

Opportunities	Threats
- Higher flexibility and interoperability - Not dependent on a single supplier - Implementing new tools and systems becomes easier if the middleware is appropriate	- System replacement is expensive - Maintaining the integrations between different systems can be very difficult - Supervising and controlling the use is difficult - In a worst-case scenario, updates or changes in one system affect all the other systems - Tools are difficult to replace, unless they are standardized - Every tool must be customized - Data errors are hard to find and correct as the web of databases is difficult to manage

At the moment the legacy architecture is the most common, as single source bundles and the middleware needed in a service-oriented architecture are difficult to implement at present. Therefore the scenarios of changing from a legacy architecture to either single source or SOA are most probable and realistic. Also a change from single source to SOA could be possible, if for example a company wants to expand its PLM architecture to the whole extended enterprise, in other words the subcontractors and other companies in the supply chain who use different PLM tools and systems.

3.6. Conclusions

The strengths, weaknesses, opportunities and threats listed in the tables above indicate that SOA has several benefits when compared to the other two architecture types. The drawback is the difficulty of not only implementation but also administration and maintenance of the architecture. Bergsjö et al. (2006) address several other issues regarding system architecture. They question whether and how far a single PLM supplier should be relied on; is it acceptable to have less functionality in order to have better integrated system architecture; will there be major changes in systems in the future; should tools and systems be customized to fit the process or vice versa; and whether it is necessary to have all the departments and disciplines integrated, or would it be possible to work with subsystems. It would also always be worth determining the return on investment (ROI) of a PLM implementation project.

In an optimal scenario, the service oriented PLM architecture would use standardized interfaces which each IT supplier would have to support. Another extreme would be that the supplier could force every company to work according to their PDM system logic. SOA represents a model which at best could offer superior usability, as the information services are created focusing specifically on the needs of an engineer or a development process.

4. MATERIAL AND METHOD

4.1. Introduction of the research subject

This thesis is a part of a Finnish Funding Agency for Technology and Innovation (TEKES) funded research project Future models for Digital and Global Extended enterprise (FUDGE). The general objective of the Fudge research project is to study what kind of information models and business processes best support the product lifecycle management. Typical PLM systems and their operation logic and information models are relatively easily applicable for managing mass produced standard products and standard configurations. As the case companies have product structure variants, configurable product family structures and customized products, applying PLM is a challenge. The primary objective of the research is to discover the best practices in how to use the present systems in this context.

The research questions of this thesis were found to be suitable to be a part of the FUDGE project. FUDGE provided a good setting for working on this thesis, as the project consortium consists of companies which are interesting and varied regarding PLM. All the six participating companies operate globally and have product development departments and production sites in one or more locations.

The project started in September 2010 and ends in June 2012. The schedule can roughly be divided into four parts: pre-surveys, benchmarking, analysis and reporting. Pre-surveys were carried out in late 2010, benchmarking site visits spanned from late 2010 to the fall of 2011. The benchmarking data and information collected were analysed at the end of 2011 and early 2012. The last months of the project are dedicated to writing reports of the findings of the research.

Table 4.1. *FUDGE project timetable.*

Monthly timetable of the project	
Start of the project	9/2010
Pre-surveys	9/2010 – 12/2010
Benchmarking site visits	11/2010 – 9/2011
Analysis	9/2011 – 3/2012
Reporting	3/2012 – 6/2012
End of the project	6/2012

4.2. Empirical research material

This chapter presents how, when and by whom the research material was collected, what type of material is used, how reliable and valid the material is and what are the most important sources of error.

During a nine month period in the year 2011, six enterprises were visited in order to gather benchmark information about various PLM related matters. The companies are Finnish and produce complex mechatronics products. This means the manufacturing processes and design of the products combine mechanical engineering, electronic control and systems thinking (Journal of Mechatronics, 2011). Different products, processes and organizational models lead to different product data management requirements and practices. For this reason, there was no pre-planned structure for the benchmark site visits and they consisted, more or less, of unstructured free speech about the subject. Some themes and leading questions were formed beforehand as starting points for discussion.

Data was collected by writing notes during the visits and later transcribing conversations which were sound recorded. Everything that is related to information system architecture and PLM maturity was extracted from the noted and transcribed data for evaluation and comparison. PLM architecture was mostly discussed in the presentations as a description of the current state and the plans of future IT system development and integrations. The amount of time spent discussing the architecture varied from company to company. Focus was mostly on the future (to-be) situation. Usually both the presenters and the audience were active. This lead to rich conversations and the participants most likely discovered some good PLM related practices from every site visit. This is supported by the findings of Pulkkinen et al. (2011), as they state that one reason of using benchmarking is to find the best practices among companies and to utilize the knowledge of several experts.

The most suitable way to get usable research material is to gather or have it gathered straight from the subject, which in this study are the case companies. This so called primary material is data which is not processed in any way. If such raw data is not available, the research has to be based on processed data, for example average values, statistics or public presentations. As the material in question is partially of qualitative type, it is possible that the answers are ideas, opinions, assumptions, beliefs or even deliberately erroneous information. Therefore it is impossible to have an objective view of the reality. (Olkkonen, 1993) As it is more or less impossible for the companies to let researchers thoroughly examine their PLM architecture and every system, application and tool within it, this project relies on data which was given by the representatives of the companies. Therefore the data integrity cannot be verified, but as the companies are not in a competitive situation, there is little reason for them to disseminate purposefully erroneous information.

The data gathered can be presumed to be very accurate, as the benchmark sessions have been hosted by people whose work is very closely related to the PLM system architecture. The company specific chapters 5.2 through 5.7 were sent for verification and approval to representatives of the respective companies. As stated by Pulkkinen et al. (2011), a well prepared benchmarking event on a selected company can be used to provide a more in depth view. The companies have been quite open and transparent in telling about their current situation. As the information shared for this research project is confidential, even problems which couldn't be trumpeted out in public were discussed. On the other hand, several important facts have most likely been left unmentioned. This left out information might or might not be relevant to the results of the project. For example the architecture types were partially difficult to determine, as there was little information concerning the level of interoperability between systems.

Management and employees might have dissenting views of the current PLM situation. In order to form a reliable overall picture of the research subject, it would be better if the interviewees would be from different organizational levels and positions. Overall, a more in-depth information collection regarding the systems would have been a good addition. This could have been carried out for example by interviewing the people responsible for the PLM landscapes specifically about the subjects discussed in the theory section of this thesis, in other words chapters two and three.

4.3. Research approach

The general aim of this study is to increase general knowledge of PLM architecture and its development process. In the beginning of the work of this study, a quantitative research approach was considered. Due to the complexity of the research subject and the diversity of the case companies in terms of size, maturity, field of business and the geographical area of operation this approach was set aside. According to Pulkkinen et al. (2011), it is very difficult to compare the PLM application level in details, as the needs, business contexts and the competitive edges of the companies are not uniform.

Salmi et al. (2000) argue that one difficulty in case study is that the researcher might be driven towards excessive subjectivity, which might lead to arbitrary interpretations and unfounded generalizations. They state that when collecting information, there is a risk of choosing only aspects supporting the researchers own argumentation.

4.3.1 Action-oriented approach

This thesis uses an action-oriented research approach. The aim of the approach is primarily the comprehension of the research subject, instead of trying to solve a predefined problem. Solving a problem and at the same time developing the solving method would be a constructive research approach. The action-oriented research approach is typical for researching questions regarding the internal actions of a company, meaning that the research problems are also tied to employees and their objectives and not only to hard measurable facts. (Olkkonen, 1993)

The approach is based on examination of the details from inside the subject of study. Usually, using this research approach, the examination is performed in close interaction with the staff of a company. In addition, it is possible to use hard facts acquired from the case company, such as the architectural presentations in this study. There are some subtypes of action-oriented approach, based on the involvement of the researcher in the subject of the research. The researcher could only be an observer, they could participate in the action they are studying, or even strive to have an influence on the subject and change with their own actions. In the latter form, the goals of the researcher might affect the result. (Olkkonen, 1993)

According to Olkkonen (1993), this research approach is not tied to any particular methodological norms or guidelines and it is difficult to structure this kind of study in advance. The main challenge of this approach is the generalization of the results, as the amount of comparison data is relatively low (Olkkonen, 1993). The possible generalization for a broader group can be made by judging and analysing the analogies between the results of the case study and the characteristics among a broader group.

The results should be considered more or less hypothetical and further studies should be performed for validation. Olkkonen (1993) argues that the contribution of a research is at the discretion of the scientific community. Using the action-oriented research approach, the difficulty of verifying the results is apparent. Often verification is not even possible. (Olkkonen, 1993)

4.3.2 Benchmarking

As the research seeks a better understanding of a real business phenomenon, an empirical approach was chosen in addition to the theoretical background. The material of this research consists of six cases, corresponding to the amount of companies involved in the project. The case companies chosen represent somewhat typical examples of system architectures in Finnish manufacturing industry, but there are also some cases which do not share the same PLM strategies, for example because of their unique product lifecycle or the history of the company.

In case studies the material gathering and analysis phase are linked. When investigating the collected information or data, it is possible to recognize a need for additional material. When working towards the final results, case studies typically alternate between material gathering and its analysis. (Salmi and Järvenpää, 2000)

Salmi and Järvenpää (2005) argue that as there are no general rules for case studies, there is a risk of excessive subjectivity. They emphasize that it is especially dangerous to end up choosing the viewpoints from the material in a biased way only to support the argumentation of the researcher.

According to Salmi and Järvenpää (2005), the researcher’s confidential and unrestrained access to information of a company and its actions is essential for a successful result. When choosing more than one case it is common practice to select opposing cases (Salmi and Järvenpää, 2000). In this study, for example the architecture or design and production methods differ between the case companies.

4.4. Conclusion

The following empirical part of the thesis is aimed to help find answers to the research questions: "*What does the PLM architecture consist of and how are the systems integrated?*", "*How do the differences in company needs and business context affect the application of PLM?*" and "*How do the shortcomings in the information systems impact the effectiveness?*"

Benchmarking was found to be an effective research method. The information gathered in the pre-surveys and benchmarking site visits was examined and all the issues related to the subject of this thesis were collected. This information was then reflected to the PLM maturity, PLM integration and PLM implementation models discussed in chapters two and three.

5. RESULTS

5.1. Structure of the results

In the following subchapters, the case companies are introduced and observations of the companies are compared to the maturity models, integration approaches and architecture models presented in chapters two and three. As the fields of business, business models and company sizes vary, there is no reason to rank the companies based on their PLM evolution.

After this introductory chapter, each case company is evaluated in terms of PLM maturity and evolution, PLM architecture and integrations within the architecture, PLM related challenges and potential future objectives and improvements. These evaluations are found in chapters 5.2. through 5.7. In chapter 5.8. the architecture and integration types are summarized and differences between the companies are discussed.

5.2. Case Company A

Company A is an original equipment manufacturer. Its product portfolio consists of standard, configured, partially configured and built-to-order products. This equipment manufactured add up to approximately half of the company's net sales. The other half consists of services business.

5.2.1 Maturity

Of the six case companies, A could be considered to be one of the more mature ones regarding PLM. PDM implementation began in the 1990's in Finland and has since extended worldwide.

The company management is committed to the development of PDM and PLM in general, and they have a PLM strategy and PDM policy in operation. PLM is used as a quality management tool and the company has also established a designated organization for the management of product data. The firm acknowledges the need for the use of new methods for the product development in order to create better solutions in the future. The company also recognizes the increasing importance of taking the product lifecycle costs in every development step into account. This means that PLM is seen as a business problem spanning the whole product lifecycle.

During the years of implementation, Company A has also had several integration projects between EDM and PDM, or PDM and ERP. There are integrations between PDM tools and an advanced one-way integration between PDM and ERP. PLM works on a cross-departmental level. These are all features of the second best level in the maturity model in Table 5.1.

Overall, Company A could be considered to be in level C, as there is relatively good understanding of PLM companywide and the tools and systems used are integrated on a cross-departmental level.

Table 5.1. *PLM maturity level of Company A.*

	Level A	**Level B**	**Level C**	**Level D**
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	Company-wide understanding of the importance of product data is taking shape	**PLM is seen as a business problem spanning the whole product lifecycle**
Involvement and understanding	From few to no people involved	Few people understand PLM	**It is clear for everyone where the company is and where it wants to be**	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple departmental integrations between some PDM tools	**Integration between PDM tools and simple integrations with for example ERP**	PDM tools are fully integrated and there is widespread integration with related systems such as ERP
Level of interoperability	Between individual tools only	On a departmental level	**On a cross-departmental level**	Across the extended enterprise
General description	There is no PLM investment and individual legacy systems are used.	PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.	**PLM is understood relatively well and integrated on a cross-departmental level**	PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.

5.2.2 Architecture and integration type identification

PDM is in large scale use in development, production and support. The company has three main systems: CAD for 3D design, EDM for design data management and PDM for product data management. In Company A, the difference between EDM and PDM is that PDM is considered as a repository for usable data, rather than a working platform for unfinished items in development. In addition to these three systems, there are more CAD systems, two other ERP systems, a supply chain management system and other tools such as a sales configurator.

CAD and EDM systems are integrated to PDM with a two-way integration. Company A has introduced a new ERP system to their IT architecture, which brings challenges because of the modifications to processes. PDM is integrated to ERP with a one-way integration. The interface is designed to prevent erroneous data from being added to ERP.

In conclusion, the current architecture can be determined to be a fairly progressive legacy architecture. The systems are in a loose integration, meaning that each system has its own functions and local data storage.

Table 5.2. *The strengths and weaknesses of a legacy architecture.*

Strengths	Weaknesses
- No need for change, users can work with the sub-systems and processes they have used earlier - A sub-system can be replaced without effect on other sub-systems - “If it works, don’t fix it”, the old architecture is familiar for everyone	- Manual data exchange between the sub-systems is time-consuming and leads to loss of data or data quality deterioration - Complex management as there is a large amount of separate databases and the same data is represented in more than one database - Competitors might implement a more efficient PLM architecture, which leads to falling behind on development - Point-to-point integration leads to complex, inflexible, unsustainable and unreliable architecture with prohibitively high costs

5.2.3 Challenges

Company A reported the following challenges regarding PLM. The amount of users of the various systems increases all the time. Especially the number of viewers is growing. The EDM environment enables editing, but as the item is moved to PDM or ERP, it is more or less locked. If erroneous information is transferred to the new ERP, it would be very difficult or even impossible to correct the mistakes in the documents or data.

The following data, information and knowledge are outside the PLM system: simulation material and results, customer information, supplier information, brochures, usage and maintenance instructions, customer feedback and product development project management such as memos, requirement definitions, reviews and surveys. In order to integrate these to the product lifecycle management, more cooperation between departments is needed. Collaboration with the suppliers exists. For example product data such as drawings and BOMs is available. However, these system integrations are restricted to one direction only, which makes it difficult for the supplier to give feedback. Improvement of the usage instructions, for example, for finding the correct information is still needed.

5.2.4 Prospects

In the future Company A plans to continue to reduce the number of systems. For example, there have been more than hundred ERP systems at most. Now the company is working toward replacing them with only one. CAD systems are being replaced by a single system. This system is from the same supplier as the EDM system used. The possibilities enabled by this implemented EDM will be used to develop collaborative product development.

The focus of PLM systems usage will be widened even more to comprise the entire lifecycle. For example better and more efficient use of 3D-models will be made in maintenance and production planning. The company will also work on integrating requirement management and product testing as a part of product data management.

As there are systems from several software suppliers, company A will retain the loose integration model. The to-be situation will lean more towards best-in-class, rather than legacy.

5.3. Case Company B

Company B is a global company, which operates mostly on the pure project business. In some projects partially configured products are used. The company operates in a field where service business is of significant importance and thus a big part of the net sales. The company has grown mostly through mergers.

The company has three main product types. The first one can be considered to be the forerunning sector in product development, project deliveries, product configuration, product data management and production. The other main product type is somewhat lagging behind in the development of the previous activities, but is nevertheless a significant part of the product portfolio. The third product is the aforementioned service business, a sector which is growing at the moment and also in the future. Company B decided long ago to create their own service infrastructure. Preventive maintenance is one of their key business factors.

5.3.1 Maturity

Company B states that PDM systems are typically designed for mechanical design, but that the company would like it to be functional also for project operations. Although product data systems have been used for more than fifteen years, Company B started thinking more about PDM in 2005 and officially started a major PDM project in 2007 by implementing a new database solution and integrating it to their CAD tools and an existing database. The tools in use as well as the work methods vary between locations and departments.

Company B has not been striving for a Big Bang type of implementation, instead having a four phase plan for the full implementation of PDM. The company had an ambitious target of keeping the duration of each phase to less than one year, but the project timetable has stretched. The project is now in its second phase. Implementation was started in a limited number of organizations located in Europe, but will gradually be continued corporation-wide. In the second phase delivery centres, more products and external design partners are and will be included. In the third and fourth phase the goal is to have PDM functional for all factories, manufacturing partners, service planning and sales, operations and service centres, and all the other functions requiring any access to product knowledge.

One of the current goals of Company B is to get the upper management to become more conscious of the importance of PDM. The company has a global organization for information management with 200 employees who work among other things as system architects and technology experts supporting 17000 users. Company B also has a designated organization for PDM development, consisting of five employees in Finland and ten in China.

Company B acknowledges that product data is used by design engineers, production engineers, sales organization, delivery organization, users and operators and service technicians, in other words by everyone involved in the lifecycle of a product. The products are used for 30-40 years and require maintenance throughout their lifecycle. Company B states that information quality should be prioritized, in other words the correct information needs to be delivered to the correct people.

As a basis for implementation, Company B has defined that PLM consists of processes, data, applications and users, all of which have to be defined before the architecture is determined. The company has defined the following as the main focus for PLM: the innovation and product development process, product information and configuration throughout its life, manufacturing processes and digital manufacturing and lastly collaboration between all engineering domains. The main focus for ERP is finance, HR and procurement, order management processes, forecasting and planning process and logistics and inventory management.

Table 5.3. *PLM maturity level of Company B.*

	Level A	**Level B**	**Level C**	**Level D**
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	**Company-wide understanding of the importance of product data is taking shape**	PLM is seen as a business problem spanning the whole product lifecycle
Involvement and understanding	From few to no people involved	**Few people understand PLM**	It is clear for everyone where the company is and where it wants to be	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple departmental integrations between some PDM tools	**Integration between PDM tools and simple integrations with for example ERP**	PDM tools are fully integrated and there is widespread integration with related systems such as ERP
Level of interoperability	Between individual tools only	**On a departmental level**	On a cross-departmental level	Across the extended enterprise
General description	There is no PLM investment and individual legacy systems are used.	**PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.**	PLM is understood relatively well and integrated on a cross-departmental level	PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.

5.3.2 Architecture and integration type identification

Earlier no suitable single source type PDM solution was found, so Company B decided to create a new one in-house. Nowadays the architecture could be defined as a legacy system, which has been gradually created from partially self-made fragments. They have also made several company mergers, which have led to a heterogeneous architecture with little integration. At the moment, the company has several PDM systems in use.

Company B states that nowadays PLM suppliers have started to focus more on business processes and to offer service-oriented architectures and suitable interfaces. Thus a need to tailor the systems exists no more. Instead, the system can be configured to some extent to function as desired.

The IT architecture is divided in to two main branches: PDM and ERP. Company B defines PDM to be data centred and to include product data management and product development. To separate the processes, PDM can be split into PDM for the product process and PLM for the order-delivery process. The business centred ERP includes finance, resources, forecasts and logistics. Marketing, sales and distribution, materials and resources and customer service are however outside ERP. These two branches reportedly support each other and even have manufacturing as a shared activity.

Company B states that the applications within PDM develop fast compared to consolidated ERP capabilities. There is also a challenge in defining where to draw the border line between PDM and ERP in the future. At the moment the amount of interoperability is limited. The main CAD system is integrated to PDM, which has been easy as both of them are from the same software supplier and little customization was required during the implementation. Also the new PDM is integrated with the old data management system, which was created in-house. The company has also begun integrating major CAE tools to the PDM system.

Company B is working their way out of legacy architecture with a best-in-class integration type of approach by decreasing the amount of redundant systems and tools. The company has loose integration between some systems and full integration between one CAD and the latest PDM system.

5.3.3 Challenges

As the products of Company B are developed and produced as projects, it creates challenges for the users of PDM. In some cases, Company B is not the main contractor of a project, which makes managing the product data of the entire project very difficult. The systems must be able to support partners and subcontractors. As a prerequisite for the previous, the systems must also be secure and there must be an ability to control access. At the moment, the products of Company B’s suppliers are not managed by the PDM system.

The amount of organizations around the world creates challenges for the operation of PLM systems, as different departments have various methods and tools. The complexity of the business processes, the organizations and the products challenges the systems and their users. Solutions created might not be universally effective, as there are different courses of action and methods in different organizations globally.

There is a great amount of PDM systems in use and one goal is to harmonize them to reduce redundancy and duplicates. Even though the products are well documented, the possibility to extract product data from them is a challenge. One of the current goals of Company B is to advance from document management to data management. Some parts of the organization have become more efficient with PDM, but some are still facing problems. For example collaboration in design and development would be beneficial, but the systems and tools are not yet used in the optimal manner.

5.3.4 Prospects

Company B has expressed their interest in the Service-Oriented Architecture model. In their future vision all the tools, such as CAD systems, will be integrated into a global solution. The company is also hoping to be able to integrate the databases to work in synchronization. New PLM tools will also be implemented, for example a customer could be able to configure the product they are buying themselves.

Company B hopes to be able to reduce the number of ERP systems to just one, so the users could trust that the information they acquire from the system is up to date. The company will also have to decide which amount of PDM systems they wish to have in the future. There has been discussion whether the two main product types and services should all have separate PDM systems or should a single shared system cover everything. The cost of harmonizing all the data into a single database is known to some extent, but the benefit and the return on investment of such a project is unclear.

The architecture type is planned to move towards either SOA or single source architecture formed around the new PDM, which is already properly integrated with the main CAD system. Also the reduction of redundant systems is about to steer towards a best-in-class integration. Shifting from legacy to SOA would require a great amount of work as the needed middleware does not exist at this time.

Table 5.4. *Scenario #1: List of opportunities and threats if the legacy architecture is replaced by a single source architecture.*

Opportunities	Threats
- Using only one database ensures data correctness and simplifies security management - Tools used can reach all the data, as it is stored in a single location - Can be based on a single supplier - All product information across the product lifecycle is stored in a central system making the product lifecycle become transparent enabling proper decision-making concerning a product. (Batenburg et al. 2005)	- A sub-system can no longer be replaced without effect on other sub-systems - Requires either heavy customization of present sub-systems and processes or adaptation to new tools and processes. - Very difficult to extend or integrate with other applications (Silcher et al. 2010) - System replacement is expensive - Relying on a single PLM bundle supplier is risky - Change resistance leads to leadership challenges - Need for major change, users can no longer work with the sub-systems and processes they have used earlier - Implementation project includes a risk of failure - Hard to realize due to distributed nature of engineering work (Bergsjö et al. 2008)

Table 5.5. *Scenario #2: List of opportunities and threats if the legacy architecture is replaced by a service-oriented architecture.*

Opportunities	Threats
- Higher flexibility and interoperability - No need for engineers and other users to learn to use new tools, because of the possibility to integrate legacy sub-systems - Enhanced collaboration possibilities - Faster product development time	- Maintaining the integrations between different systems can be very difficult - Tools are difficult to replace, unless they are standardized - Every tool must be customized

5.4. Case Company C

Company C has a number of different product types: standard, purely configurable, partially configurable and project products. In addition, they also have a significant service business.

In one product category, almost all the product development is outsourced. This includes approximately forty design engineers. Only the product development management and a core team are employed by Company C for the purpose of keeping the knowledge within the company. Training of the new designers recruited is performed by the subcontractor. If there is a larger change, for example in a process, then Company C will train the subcontractor. This product category is approximately 30% project and 70% configurable products.

The designers of another category are typically entrepreneurs with a long career and a good deal of experience. They are located all around Finland and are working from small offices, sometimes also from home offices. Managing such a group of designers is difficult. The subcontractors have been given the same access rights to product data as the other designers. In this category, all production is in done with an engineer-to-order approach.

5.4.1 Maturity

When a new business system development project is started, it is headquarter driven and will later be implemented globally. However, for the current ERP implementation, the company has a global expertise team.

Mechanics, electronics and software are all currently managed in separate systems as separate models. This kind of silo orientation might hinder collaboration between departments.

Table 5.6. *PLM maturity level of Company C.*

	Level A	Level B	Level C	Level D
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	**Company-wide under-standing of the impor-tance of prod-uct data is taking shape**	PLM is seen as a business problem span-ning the whole product lifecy-cle
Involvement and under-standing	From few to no people involved	**Few people un-derstand PLM**	It is clear for everyone where the company is and where it wants to be	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple depart-mental integra-tions between some PDM tools	**Integration between PDM tools and sim-ple integra-tions with for example ERP**	PDM tools are fully integrated and there is widespread integration with related systems such as ERP
Level of interopera-bility	Between indi-vidual tools only	**On a depart-mental level**	On a cross-departmental level	Across the ex-tended enter-prise
General description	There is no PLM investment and individual legacy systems are used.	**PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.**	PLM is under-stood relatively well and inte-grated on a cross-departmental level	PLM is inte-grated across the supply chain. PLM is utilized in state-of-the-art ways, for ex-ample in a closed-loop fashion.

5.4.2 Architecture and integration type identification

Company C describes their PLM to consist mostly of item configuration, design data management, change management and structural content management. PLM system architecture includes a PDM system and various CAD systems. Currently they have an older PDM system serving as a publishing platform, which is connected to EDM. The current EDM, which will be the future PLM backbone, is used mostly in an out-of-the-box fashion. All the redundant functionality has been or will be removed.

Company C used to have dozens of ERP systems and now they are trying to reduce the number to just one. The current main ERP will be replaced by a new one. This transition is already in development. The IT platform also includes a customer relationship management system and a knowledge management system, which is used only to gather tacit knowledge.

There are several CAD systems in use, varying from an organization to another. Designing a product might require the use of various CAD systems, for example 2D and 3D CADs. The current ERP system is beginning to make room for the new one. There are multiple separate installations worldwide and integration is to one direction only. The IT landscape can be identified as a legacy architecture, as there is a large amount of systems in use having limited integrations between one and another.

5.4.3 Challenges and prospects

Company C grows also through company mergers and the growth creates challenges. The company needs to create a plan the implementation of the products and IT tools of the acquired companies. Company C also has the same problem as Company B: how to harmonize all the product data and how to integrate service business. Company C states that technical solutions, such as new systems, are generally not too complicated to implement, but it is very challenging to combine them.

In the future, Company C will develop cooperation with their subcontractors. Either there should be a web-client or something similar for the extended enterprise or a direct access allowed to the systems of Company C. The new PDM system will become the PLM backbone, including product data management functions, and the old PDM will be replaced with a PDM module for the new ERP. All the CAD systems will be integrated into the new backbone. Also the sales configurator will be integrated into the new ERP and PDM. The new ERP system will provide an access point for all the component orders and will be integrated into PDM most likely in a two way integration. There will be some other smaller scale integrations, which have not been thoroughly defined at the time of this study.

The number of systems will be reduced and the architecture is going to resemble a best-in-class integration even more, or even a one system as an integrator type of model with the future PDM being the integrating backbone. CAD integration to PDM will remain peer-to-peer, but all other integration from PDM will be made through common middleware. New PDM system also enables Company C to utilize service-oriented architecture and the architecture is being revised to get benefits in this area.

5.5. Case Company D

Company D is a manufacturer of partially configurable and configurable projects in addition to the services business, which the company has industrialized during the last twenty years. The company operates in more than fifty countries.

Product lifecycle management in Company D consists of management of the products, management of their customers' equipment and lifecycle challenge management, which includes innovation and change related affairs. At the moment the company focuses on developing their IT landscape from a complex organized chaos towards more of a single source PLM foundation.

5.5.1 Maturity

Company D considers PLM to include the following product related activities: design, production, usage, maintenance and modernization. The opinion in the company is that PLM is focused more on the processes and organization rather than the tools used.

The history of the systems dates back to early 1990's, when an EDM was created as a document management backbone, although no item or configuration management was established yet. The products, both physical products and service contracts, of Company D are always configurable, so there is a need for configurator systems. Shortly after the beginning of the millennium, the company started the implementation of a basic PDM system. Company D's PLM program was initiated few years after. The company grows usually through service company mergers, which means only ERP data needs to be implemented. In reality, PDM and ERP organizations are rather far from each other.

Table 5.7. *PLM maturity level of Company D.*

	Level A	Level B	Level C	Level D
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	Company-wide understanding of the importance of product data is taking shape	**PLM is seen as a business problem spanning the whole product lifecycle**
Involvement and understanding	From few to no people involved	Few people understand PLM	It is clear for everyone where the company is and where it wants to be	**Widespread understanding of PLM in the company and in its extended enterprise**
Integration	No integration	Simple departmental integrations between some PDM tools	Integration between PDM tools and simple integrations with for example ERP	**PDM tools are fully integrated and there is widespread integration with related systems such as ERP**
Level of interoperability	Between individual tools only	On a departmental level	On a cross-departmental level	**Across the extended enterprise**
General description	There is no PLM investment and individual legacy systems are used.	PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.	PLM is understood relatively well and integrated on a cross-departmental level	**PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.**

5.5.2 Architecture and integration type identification

Company D divides their process solution landscape into several parts connected to each other. The Back-end includes content, CADs, PDM and ERP, which are all connected as seen in Figure 5.1. ERP is connected into business intelligence. Front-end includes customer related functions, such as sales configuration, spare part store and call centre. Front-end is connected to Customer and Delivery Process and Field operations. Field operations is connected to Supply operations, which connects back to Back-end.

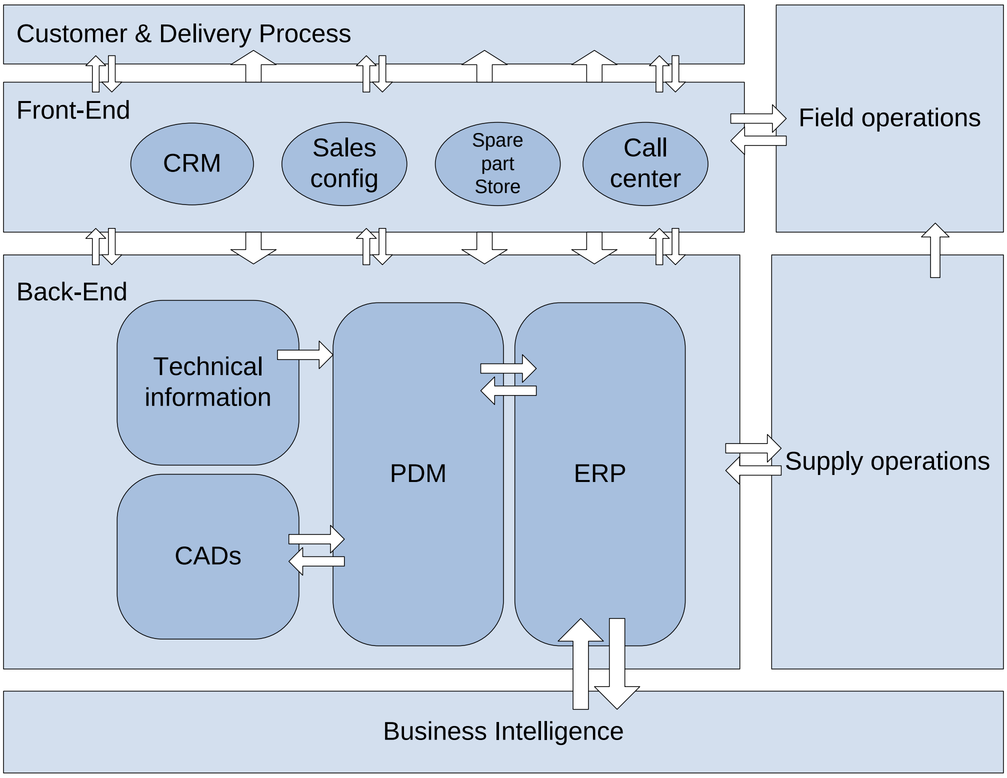

Figure 5.1. *Simplified adaptation of the functional chart of PLM of Company D at the time of this study.*

The PLM architecture of Company D has been developed for a fairly long time and can be considered to be fairly advanced. There are several integrations between the CAD tools, EDM, two PDM systems and ERP. Emphasis is on the integration of the mechanical CAD. Electronics CAD is following behind. The product design process depends on the amount of engineering and configuration needed. This leads to several combinations of systems being used for different product types.

The version of ERP they have used up to this point has been customized widely. Now as they are implementing a later version of the same system, they are trying to refrain from customizing it.

Integration type can be identified to be of a loose and peer-to-peer type. In other words, data is stored in development discipline specific databases and the intercommunication is done from one peer to another, instead of transferring the data through a dominant system. However, manual data exchange is still required between some systems.

5.5.3 Closed-loop adaptation

Company D has successfully utilized the idea of closed-loop PLM introduced in chapter 2.3.4. The company has a program, the objective of which is to chart the condition of the products they maintain and to pre-emptively find out if any problems exist and to inform the customer of the need of service. There are however some challenges in managing the product data of the competitors' products Company D services. No 3D models of products of the competitors' are available, although some photos and other scarce information exist.

The service contracts and orders are linked to delivered products in ERP. When a maintenance technician has visited a site, they will note down in the system that the service order is finished and when necessary list the parts that were replaced. These service reports and feedback are used for identifying replaced or malfunctioning components and are taken advantage of in the beginning of lifecycle activities in the future. The maintenance technicians are allowed to receive certain basic information of their current maintenance call to their personal digital assistant (PDA).

5.5.4 Challenges and prospects

Since the company's two major business lines are new products and services, the different requirements of these two lead to challenges in PLM, as the IT systems tend to focus on the actual products. Therefore proper management of immaterial products, such as services, is found to be very difficult. This leads to massive customization of these systems. Company D uses components from several thousand different manufacturers, which is very challenging for the product data management.

If the integrations do not work optimally, there is a problem of departments becoming individual silos. This means the different parts of the organization are not able to cooperate as well as they should and are not able to know what is occurring in the other systems, for example PDM or ERP. These kinds of organization and process related challenges are dangerous for example during a component shortage. Keeping both up to date requires much effort. Company D is figuring out ways to get PDM and ERP to work together more efficiently, as for example PDM does not have sufficient functionality to manage component storage balance or costs.

As an organizational challenge, the lack of transparency between organizations is an undesirable situation. If local plants are given more power to customize lifecycle functions, there will be transparency problems between product development and the supply chain. On the other hand, access management is found to be too strict in one PDM system. There is also no as-delivered BOM saved in any system, as some of the parts of the BOM are only in the systems of subcontractors. Also the industrial design organization will be integrated to the mechanical CAD. At the moment there is no tight integration between these systems, processes or organizations. This integration will be realized when the software and concept design are capable for it.

The desired future situation is that there would be a two-way integration between CAD systems and PDM and also between PDM and ERP. Company D is moving towards a single source PLM foundation.

5.6. Case Company E

Company E has a number of different product types: standard, purely configurable, partially configurable and projects with partially configurable products. In addition, they also perform service operations. The products can be defined to be the most purely configurable of all case companies' products. The lifetime of a Company E product is long and spare parts are available for ten to twenty years. Some of the less common equipment manufactured are serviced for more than thirty years.

5.6.1 Maturity

The company has had a global PLM strategy for approximately five years. The current ERP system was implemented in the beginning of the millennium and has since been customized greatly. Since 2005, the system has had PDM functions implemented in it. Document management was moved from an old PDM system to the new one in 2011. Company E has licence management processes used for example to ensure that only information of a certain product is given to a certain plant.

The product development and production activities are distributed globally to Asia, America and Europe. Product development creates more than fifty documents daily and thousands of items are created per year. The central logistic warehouses of the company are in Europe and South-East Asia.

Table 5.8. *PLM maturity level of Company E.*

	Level A	**Level B**	**Level C**	**Level D**
Application of PLM	Non-existent	Local initiatives exist, but there is no overall vision	**Company-wide understanding of the importance of product data is taking shape**	PLM is seen as a business problem spanning the whole product lifecycle
Involvement and understanding	From few to no people involved	Few people understand PLM	**It is clear for everyone where the company is and where it wants to be**	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple departmental integrations between some PDM tools	Integration between PDM tools and simple integrations with for example ERP	**PDM tools are fully integrated and there is widespread integration with related systems such as ERP**
Level of interoperability	Between individual tools only	On a departmental level	**On a cross-departmental level**	Across the extended enterprise
General description	There is no PLM investment and individual legacy systems are used.	PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.	**PLM is understood relatively well and integrated on a cross-departmental level**	PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.

5.6.2 Architecture and integration type identification

The architecture consists of three different parts all within one system. The three parts are: PDM for product data and product structure, Document management for documents and Data storage for sales reporting and product certificates. This means both ERP and PDM are operating in the same system and have a two-way integration between them. There is also a separate CAD data management, or EDM, system between the CAD tools and PDM. There is a two-way integration between the EDM and the PDM systems. Software related tools are connected to a software configuration management (SCM) system, which is again connected to the main PLM system. The architecture type can be defined to be a hybrid of a one system as an integrator and a single source type of architecture.

Generally all the data is gathered to a single location globally and from there distributed to local departments. The product data is in ERP and product licence information is used to allow and deny access to the extended enterprise using it. For example factories only see the local items they manufacture.

Engineering data is stored in design area specific EDM/PDM, i.e. mechanical design data is in its own repository as well as embedded software or hardware design related data. Design drawings are published in ERP, which is the master for user processes.

Service business is also managed in the main PLM system. There is a dedicated Products Installed base as the search location of all service, maintenance and warranty information. This data is also stored in Data Storage, meaning the equipment certificates are updated through a web-interface. If there is no Internet connection, the service technician is able to create an offline-copy of the needed product information for his own computer or PDA.

5.6.3 Challenges

Earlier, before a major PDM project, Company E analyzed the state of and challenges in data and information exchange. The company found out that a lack of set standards for the saved data and information had led to inefficient search functions. Also after sales customer support was found to be difficult, as information was not easily available. In other words, process automation was difficult as information was scattered around the systems.

Even though globally all the information should be in a single location, there are still local variants in existence, from which information cannot be acquired globally. Also the quality control is performed manually and there are different processes for it in different locations.

Company E representatives argue that the actual tools are relatively easy to get to work as wanted, but the difficulty lies in getting the people to follow the processes.

5.6.4 Prospects

Future development objectives include several tool and process related improvements. Company E has a goal to standardize their product data and to maintain data quality by developing the tools currently in use. The company also strives for unified and common actions and processes. They are also going to improve usage monitoring.

Company E is planning to define the processes more clearly, for example how data is created and how it is maintained and managed. There will be a product information concept, which is created for global information management, which includes item, change and equipment certificate management. The goal is to have fast, effective and controlled data distribution, to automate processes and to standardize legacy data. In other words, Company E is focusing on improving the current state, rather than creating new methods or making drastic changes to the architecture.

Table 5.9. *Strengths and weaknesses of a single source architecture.*

Strengths	Weaknesses
- Using only one database ensures data correctness and simplifies security management	- Requires either heavy customization of present sub-systems and processes or adaptation to new tools and processes.
- Tools used can reach all the data, as it is stored in a single location	- Very difficult to extend or integrate with other applications (Silcher et al. 2010)
- Can be based on a single supplier	- System replacement is expensive
- All product information across the product lifecycle is stored in a central system making the product lifecycle become transparent enabling proper decision-making concerning a product. (Batenburg et al. 2005)	- Relying on a single PLM bundle supplier is risky
	- Implementation project includes a risk of failure
- A truly integrated controllable system where data are represented in only one place (Bergsjö et al. 2006)	- Hard to realize due to the distributed nature of engineering work (Bergsjö et al. 2008)

5.7. Case Company F

The business field of Company F consists of project, configurable project and partially configurable production, and thus resembles the operation of Company B. Production is carried out as make to order, which means the manufacturing starts only after the order is received.

There is considerable global competition, and production time and costs constantly need to be reduced. Company F has product development in four continents and the operations are becoming more global and the company is striving to get closer to the customers. The company has service business centres in three and service operations in dozens of countries.

5.7.1 Maturity

A typical project of Company F lasts for circa two years and the typical product lifecycle lasts from 25 to 30 years. The company believes that a single PDM system would not be able to manage the whole lifecycle of a product or a project and that a PDM system could only be used to manage the final results of a project. Production sites look up drawings from the CAD tools, as the design is usually unfinished when the base production begins.

Company F considers PDM to be a platform in which various tools work together. The company argues that a common database would bring transparency to the design and development phase, and emphasizes that software and network connections must be stable and faultless.

Through several projects in the history, a large number of library components have been created and stored in the PDM system. These components can be reused in certain process solutions. On the other hand, using previous projects as templates is found to be dangerous and counterproductive, as previous mistakes would be reproduced.

Subcontractors have limited access to see the documents of the project they are working at. There is a risk of data leakage, however so far no problems have emerged. They are using the main document management system via tunnelled connections secured through a firewall. Subcontractors are trained by Company F representatives to use the document management system.

Table 5.10. *PLM maturity level of Company F.*

	Level A	Level B	Level C	Level D
Application of PLM	Non-existent	**Local initiatives exist, but there is no overall vision**	Company-wide understanding of the importance of product data is taking shape	PLM is seen as a business problem spanning the whole product lifecycle
Involvement and understanding	From few to no people involved	**Few people understand PLM**	It is clear for everyone where the company is and where it wants to be	Widespread understanding of PLM in the company and in its extended enterprise
Integration	No integration	Simple departmental integrations between some PDM tools	**Integration between PDM tools and simple integrations with for example ERP**	PDM tools are fully integrated and there is widespread integration with related systems such as ERP
Level of interoperability	Between individual tools only	**On a departmental level**	On a cross-departmental level	Across the extended enterprise
General description	There is no PLM investment and individual legacy systems are used.	**PLM is realized as individual applications integrated on a departmental level. There is no overall PLM vision.**	PLM is understood relatively well and integrated on a cross-departmental level	PLM is integrated across the supply chain. PLM is utilized in state-of-the-art ways, for example in a closed-loop fashion.

5.7.2 Architecture and integration type identification

Company F operates from a perspective that a base for every product is its functionality. Through the functionality they move on to the structure of a product, in other words all the mechanical aspects, to see what kind of mechanical solutions are needed to support the functionality. The company argues that a single PDM would not be able to offer all the functions required and thus more than one system is needed.

The system architecture consists of CAD tools connected to the design system, which functions as the company PDM platform. The tools share a common meta-data repository and thus information is exchanged automatically between them. This system is used by all offices and subcontractors. It has only a single database for everyone, thus making management and control easy. This PDM platform is then connected to the corporation-wide PDM with a two-way integration and to ERP with a one-way integration. In addition, they have a document management system and several self-made Microsoft Excel based tools, for example for dimensioning and configuration.

Integrations exist, but the interoperability is not fully utilized as the project business creates challenges for IT systems in comparison to for example standard products. However, Company F acknowledges that there is room for improvement regardless of the business field. The IT landscape can be defined to be a legacy architecture. Company F has one system as an integrator, in other words the PDM platform functions as a data hub for most of the tools.

Table 5.11. *Strengths and weaknesses of a legacy architecture.*

Strengths	Weaknesses
- No need for change, users can work with the sub-systems and processes they have used earlier - A sub-system can be replaced without effect on other sub-systems - “If it works, don’t fix it”, the old architecture is familiar for everyone	- Manual data exchange between the sub-systems is time-consuming and leads to loss of data or data quality deterioration - Complex management as there is a large amount of separate databases and the same data is represented in more than one database - Competitors might implement a more efficient PLM architecture, which leads to falling behind on development - Point-to-point integration leads to complex, inflexible, unsustainable and unreliable architecture with prohibitively high costs

5.7.3 Challenges

The current PDM system is a derivation from a different business field and thus not suitable for the operation of Company F. Also their ERP system is dictated to be the one currently in use.

The company has general challenges typical to a legacy architecture. Company F has challenges in the information flow to and from their subcontractors. Users have to enter the same information to the systems more than once, which leads to a risk of information quality deterioration. The company argues that finding information should be made easier and that the services business should operate more efficiently. For example, there have been cases where competitors have made changes to the Company F products during maintenance calls. Keeping track of the state of the products is therefore very difficult. The products of Company F are more complex than the ones by Company D, thus there are more components and assemblies which might be repaired or replaced. Company F is also under pressure to shorten the production time of their products. However, some of the needed components bought from suppliers might take very long to arrive.

The design system used, which also serves as the PDM platform of the company, is relatively unknown in Finland due to its novelty. Therefore there is a lack of engineers who know how to use it. The subcontractor designers need to be trained in order to get them to use it. In comparison, the CAx system of Company F is more familiar to many and only the Company F specific differences need to be taught. There are also big cultural differences in product development and design between countries.

There is a lot of tacit knowledge around, but gathering and managing it is a challenge. The ones who possess the knowledge are busy fixing current errors and working on the projects.

5.7.4 Prospects

Company F presented a list of additions and improvements they need to or have planned to realize. Considering the scope of this research, one of the most important plans the company has is to improve integrations between systems. Existing integrations between CAx tools, PDM platform, PDM, ERP and so on are hoped to be developed into two-way integrations. Company F plans to harmonize the work processes, in other words they aim to have common tools and processes for everyone. The company also has a goal to reduce the number of systems. These improvements would make design and production non-dependent of the production country or plant. Project load should also be managed in a better way and collaboration and receiving help from other offices should be encouraged. Engineers could possibly work on more standardized products in the future, if they would be less busy working on make-to-order projects.

Company F is planning to put a new PDM system into operation for managing production, procurement and maintenance documentation among other things. The PDM platform will be redeveloped, extended, and better integrated into the corporate PDM and ERP system. This would improve the information flow and information would need to be entered only once and only to a single system. In general, the interoperability is projected to be enhanced. The PDM platform is also planned to be available on-site for giving up-to-date information during production.

Most of the previous are long-term objectives and clear strategies to achieve them were not discussed or revealed. Therefore, there will not be any major changes in the architecture model in the near future and legacy architecture will continue to represent the state of IT systems in Company F. As they argue that a single PDM system would not be able to perform all the functions needed, single source architecture would not be suitable. Moving to service-oriented architecture might be a good solution, but as product data management in the project business field is very difficult, return on investment might not be favourable. For example to have the whole extended enterprise use the same PLM systems would be more or less impossible, as there is a vast amount of business partners, suppliers and subcontractors who are working with other companies than Company F also.

5.8. Summary of the results

All the case company presentations included definitions of the major production, architecture and integration types. This information is summarized in the table below. This table also includes the approximate service business percentage of net sales and the future target architecture and integration types.

Table 5.12. *Identification of case companies' architecture and integration types.*

Company	**A**	**B**	**C**	**D**	**E**	**F**
Production type	Configur-able, Standard, Project	Project, Configur-able	Project, Configur-able, Standard	Configur-able, Con-figurable in project	Config-urable, Standard, Project	Project
Service business' share	Half of the net sales	Less than half of the net sales	Less than half of the net sales	More than half of the net sales	*Figure not available*	Less than half of the net sales
As-is Architecture	Legacy	Legacy, Best in class	Legacy	Legacy, Peer to peer	Single source	Legacy
Integration	Loose	Loose/Full	Loose	Loose	Full	Loose/ No
To-be Architecture	Legacy, Best in class	Single source or SOA	Best in class, One system as an integra-tor	Single source	Single source, One sys-tem as an integra-tor	Legacy
Integration	Loose	Loose/Full	Loose	Full	Full	Loose

Schedules for the to-be scenarios are not definite or comparable. One company might reach its goal in a couple of years while for others it might take more than ten years. The PLM development projects require time and resources. For example, Company B is striving for either a single source or a SOA architecture, but forming one might take several years.

Several common challenges were discovered. Company mergers, in both being the company merged and merging, have created problems in the past. The amount of systems and tools has led to for example harmonization challenges. Most, if not all, PLM systems and tools still focus on the BOL activities.

Especially the project companies have difficulties in information management, as the information, data and knowledge are spread across the other participants of the project. These subcontractors might have very different product data management systems and processes, which are not interoperable. Security questions emerge when more than one company wants access to certain information. A project company might not have the necessary information for service business if the information from other participants of the project is not available.

In the tables below, the amount of circles in each cell represents the number of case companies determined to be on the respective PLM maturity level. In table 5.14. the companies with the highest and lowest average level are excluded. This balances the figure slightly.

Table 5.13. *PLM maturity level spread*

	Level A	Level B	Level C	Level D
Application of PLM		o	ooo	oo
Involvement and understanding		ooo	oo	o
Integration			oooo	oo
Level of interoperability		ooo	oo	o
General description		ooo	oo	o

Table 5.14. *PLM maturity level spread excluding extremes (companies D and F)*

	Level A	Level B	Level C	Level D
Application of PLM			ooo	o
Involvement and understanding		oo	oo	
Integration			ooo	o
Level of interoperability		oo	oo	
General description		oo	oo	

Most of the companies are found to be on either level B or C. This means the PLM realization is still in either a departmental or a cross-departmental level, but not yet extended across the supply chain.

6. DISCUSSION

The aim of this research was to study the relation between the PLM architecture and the system usage by comparing theoretical models with the discoveries from a set of benchmarked case companies. The main research question consists of three sub-questions. The answers found to these questions are evaluated in this chapter.

The first question, *"What does the PLM architecture consist of and how are the systems integrated?"*, is answered through two different methods. First, chapter 3 includes a literature review presenting different architecture and integration models. These models are compared and evaluated based on their strengths and weaknesses. In addition, the opportunities and threats in replacing one type of architecture with another were presented. The amount of literature concerning PLM architectures is limited. Therefore the architecture model review can be considered to be comprehensive. Secondly, the question is answered by examining the architecture and integration models used in the case companies in order to see how the models work in practice.

Architecture models become apparent in case companies' IT landscapes. The strengths and weaknesses mentioned in the theoretical models can be found also in the reports from the case companies. Integrations exist in each company's architecture. There is still plenty of manual interoperability, but all the case companies strive to reduce the amount of manual work and lean more towards automatic data exchange. In other words, all of the case companies are still, more or less, in a state of legacy architecture. The reason might be that all-in-one type of bundles used in single source architecture have been in the market for a relatively short period of time. Also the implementation requires plenty of resources and commitment. The same challenges occur when implementing the middleware needed in a service-oriented architecture.

Following the architecture analysis, the second question *"How do the differences in company needs and business context affect the application of PLM?"* is answered in the results chapter (chapter 5). The types of products or projects made by the companies are determined. All of the companies receive roughly half of their net sales from the service business. Service business and project products seem to be the most challenging fields in PLM, as PLM systems are designed heavily on the basis of mass produced standard products and standard configurations. For example information needed during a service or maintenance visit might not be available as it might exist only in the database of a subcontractor or a third party service company responsible of, for example, replacing a part in the past.

The third sub-question, *"How do the shortcomings in the information systems impact the effectivity?"*, is answered in the results chapter. The challenges regarding PLM maturity, architecture and integrations are studied in the case of each case company. The maturity levels differ somewhat. Common future goals were discovered: for example harmonization of data and information, reduction of redundant systems and improvement of interoperability.

The beginning of the lifecycle is the area most focused on in the currently marketed PLM systems and tools. This lifecycle phase is the most convenient to manage and control as it comprises only the data, information and knowledge creation within the company. Also the case companies' PLM systems are mostly used in BOL activities, but in the to-be situation also the EOL and especially MOL activities will be receiving more support from the tools and software.

7. CONCLUSIONS

The research subject, product lifecycle management, was discussed in the literature review part of the thesis in chapter 2 by presenting the definition of PLM, reasons for implementing a PLM strategy, requirements for PLM and systems and tools included in the PLM architecture. Then a four level PLM maturity model was put together based on the two models presented in literature. Each of the levels include a determination of the level of application of PLM, extent of the users and organizations involved in the PLM application, level of integration, level of interoperability and finally a summary of the situation as a whole.

Following the maturity model study, two widely cited models of different architecture integration approaches were presented in chapter 3. These two models were compared and similarities in the approaches were listed. Based on these two models, three dominant architecture types were discovered: legacy architecture, single source architecture and service-oriented architecture.

The benefits of architecture integration can be approached for example from the viewpoints of user satisfaction and system manageability. Engineers who use the tools prefer at least the amount of functionality they have had before, thus resisting any change which might hinder the usability of a software or system. Therefore companies keep using legacy systems or customize the new software implemented drastically. From the other viewpoint, the amount of different subsystems and tools can lead to a very difficult to manage architecture with several interoperability functions and integrations between every system.

At the moment the legacy architecture is found to be the most common, as single source bundles and the middleware needed in a service-oriented architecture are difficult to implement at present. Therefore the scenarios of changing from a legacy architecture to either single source or SOA are most probable and realistic. Also a change from single source to SOA could be possible, if for example a company wants to expand its PLM architecture to the whole extended enterprise, in other words the subcontractors and other companies in the supply chain who use different PLM tools and systems.

An overall outlook of the current situation of PLM in a considerable sample of the largest Finnish manufacturing companies is presented in the empirical section of this thesis. The material used in this research is based on six case studies, corresponding to the amount of companies involved in the research project. The case companies represent fairly typical examples of system architectures in the Finnish manufacturing industry. There are also some cases which do not share the same PLM strategies, for example when a company's operations are based on project business rather than standard or configurable products.

Benchmarking was found to be an effective research method. The information gathered in the pre-surveys and benchmarking site visits was examined and all the issues related to the subject of this thesis were collected. This information was then reflected to the PLM maturity, PLM integration and PLM implementation models discussed in chapters 2 and 3.

There would be plenty of room for further research in PLM architecture and its relation to system and tool usage. The usage could be monitored more closely for example by researching how much time and resources could be saved when switching from manual data transfer between systems to automatic data exchange. Quantitative research of the usage of PLM systems could be conducted by analyzing comprehensive database entries and logs. Using such method, the actions performed by an average PLM system user could be analyzed. This would help in finding out practical information on how the systems are actually used, which could then be compared to how the systems are designed to be utilized. Other potential areas for future research which have been discussed during the benchmarking site visits in this research project are the importance of information quality, how to improve reuse of information and how to improve data search functions.

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