Integrated information management in complex product development

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Doctoral thesis

Academic thesis, which with the approval of Kungliga Tekniska Högskolan, will be presented for public review in fulfilment of the requirements for a Doctorate of Engineering in Machine Design. The public review is held at Kungliga Tekniska Högskolan, Lindstedtsgügen 26, room F3, and at Massachusetts Institute of Technology, 1 Amherst Street, Muckley Building E40, room 208, on December 15, 2009, at 15.00 CET.
Abstract
Where do companies begin their efforts when trying to improve information management in product development? In large companies involving many people, multiple processes and highly technological products several factors have an impact on efficiency. Interdisciplinary integration and structured information are two overall proposed key factors that have been identified as important to obtain efficient information management.

Measurement of satisfaction level among information systems users is proposed as an angle of approach to identify key improvement areas from an operative perspective that are argued to be strategic for management to address. However, the need for adjustments to contextual prerequisites and a changing environment makes evaluation necessary prior to measurement. An evaluation framework is proposed to identify metrics that are tailored and kept in line with business and development strategies to ensure their relevancy.

This research has aimed at taking a holistic approach to information management in complex product development. The research focus has been on the integration between engineering disciplines where software and electrical R&D departments at automotive companies have been the main source of the analysis material.

Integrated information management entails support for activities within the engineering domain. Several strategies are discussed to manage trade-offs in organizations in order to succeed with integrated information management. A needs-based balance is one important approach proposed to resolve changing and conflicting needs. Furthermore, it is argued that operative and strategic goals should be allowed to co-exist.

Providing the right infrastructure to support designers in their everyday work does not necessarily mean additional functionality to existing information systems or automated work activities by improved document templates. Rather, it is suggested that a shift in focus (from addressing detailed requirements management to reflecting on interrelationships between information objects and system inter-dependencies) would be a strong mechanism to succeed with information management.

The transition into model-based development is argued to be a much needed change for organizations to obtain integrated information management, since a model-based approach is considered an important basis for structured information. Anticipated benefits with integrated information management are increased information availability, reduced information overflow, and enhanced communication and understanding of critical system dependencies.

Keywords
Information management, information systems, integrated product development, systems engineering, innovation management, PLM, model-based development

Language
English
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MIT, Cambridge, November 2009

– Dadadada?
– Sorry Isak, I forgot about you. Love you!
LIST OF APPENDED PAPERS

Paper A

All authors participated in the study planning and conducting of interviews. Malvius conducted the analysis. The paper was written by Malvius and Redell.

Paper B

Malvius took initiative to and planned the study. All authors participated in the study and analysis. The paper was written by Bergsjö and Malvius.

Paper C
Bergsjö, D., Malvius, D. and Christensson, C., “Measurement for information management performance in complex product development: A model to identify improvement areas based on user satisfaction”.

(Notes: The appended paper is based on a working paper that appears in the proceedings of the 5th Conference on Systems Engineering Research, CSER 2007, Hoboken, New Jersey, USA. A previous version of the appended paper has been published in Bergsjö, D. (2009) Product lifecycle management - architectural and organisational perspectives, Department of Product and Production Development, Chalmers University of Technology, Doctoral thesis)

All authors contributed in the planning of the study. The study carried out by Bergsjö and Malvius. The paper was written by Bergsjö and Malvius. Major revisions have been made by Malvius in this thesis version of the paper. These revisions include implementation of review comments made to the previous version.
**Paper D**


*The study was planned and carried out and the paper was written by Bergsjö and Malvius.*

**Paper E**


*The paper was written by Johnsson and Malvius. Norell Bergendahl took active part in the discussions and contributed with ideas and reviews. The paper was part of the PIEp Tiger Team Writing Workshop.*
LIST OF ADDITIONAL PUBLICATIONS


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1 INTRODUCTION TO THE RESEARCH FIELD

Organizations are still struggling with product development. Why? One reason is the problems organizations face with exchanging and sharing information.

Hubka and Eder (1996) define designing as “the transformation of information from the condition of needs, demands, requirements and constraints into the description of a structure which is capable of fulfilling these demands”. The transformation process is illustrated in Figure 1. The design process is frequently described as an information-driven process (e.g. Wallace and Hales 1989; Moenaert and Souder 1990; Majumder et al. 1995), and this is especially true in complex product development, where there is an increased need for more effective information flow between individuals, teams, organizations and the environment (Adler et al. 2003). It is suggested that the need to integrate “new” technology such as software and electronics into mechanically mature products makes the design process even more reliant on information activities. When it comes to defining complexity in a product development context, several definitions are offered, based on either project or product complexity (Kim and Wilemon 2003). In this thesis, complexity is defined in accordance with the definition made by Kim and Wilemon since they include both factors in their definition. Complexity is defined from a managerial point of view and considers all of the complexities likely to be encountered by people involved in development: “complexity consists of the difficulties and uncertainties, posed by the number of technologies/components/functions in development efforts and the nature of the organizational tasks that individuals and organizations face in carrying out new product development programs”. They further identify several sources of complexity (e.g. technological, market, development, marketing, organizational) and introduce a framework that enables organizational functional groups (such as R&D, manufacturing, marketing etc) to do a comparison on the sources and the impacts of complexity in product development for cross-functional impact.

![Image](image.png)

Figure 1 The design process proposed as a transformation of information model (from Hubka and Eder 1996).
The term *complex products* in this thesis refers to products that most often include software, electronic and mechanical components and which are often developed in large organizations with a need for involvement of many people with a large diversity of expertise. Hence, these products can be referred to as technology and knowledge intensive products. Moreover, complex products usually have a long life cycle and the development process is therefore often more incremental or evolutionary in its nature rather than radical. Usually, there is a platform or architecture as the basis of these products to manage the technical complexity of the product and shorten the development time and cost for a new product. However, the development time is still normally measured in years rather than months. Products developed in this context are also referred to as platform products and complex systems (Ulrich and Eppinger 2007).

Product complexity forms critical system dependencies and relationships between information objects. These system dependencies consist of integrated elements that can be products of hardware and software, people, facilities, and procedures. This is also the way systems are perceived in this thesis. Systems development and complex product development are used as synonymous concepts throughout the thesis. From a technical perspective, the need for systems integration can be exemplified by the inter-connection of several electronic control units, as in a modern passenger car, with functionality distributed over several systems and sub-systems. The number of potential bugs in a system can be overwhelming and increases steadily as more and more functions are realized by electronics and software. From an organizational perspective, product development settings consist of large organizations where different engineering disciplines, such as mechanical, electrical, software and control engineering, have to interact and collaborate. Information has to be shared and accessed by several stakeholders, which creates the need for information exchange across disciplines, across departments and across processes (Figure 2). Individuals need to understand what part they play in the system, and how their role is perceived by other members taking part in the development. In addition they have to have an understanding of the whole system and its sub-systems, and of where in the organization they belong and how they are interrelated to other team members. Changes in one system can have unexpected implications on other apparently unrelated systems, which is why it is important for designers to understand what specific influences they have in each system (Adler et al. 2003). However, different backgrounds and understanding may hinder the possibility to view a system as a whole, and instead in practice it is often considered as a sum of its different unrelated parts (Shakeri 1998).

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1 In the context of this thesis, a *discipline* refers to a specific area of knowledge related to an engineering profession, for example, mechanical, engineering or electrical engineering (defined by Adamsson 2007).
1.1 Problem understanding and research motivation

Information management relates to activities and means for searching, retrieving, sharing and storing information. Designers experience challenges in all these phases. When searching for information, differences in terminology can lead to misunderstandings with locating differently defined pieces of information covering the same thing, or (perhaps even worse) using the same term for different things. This results in a lack of confidence that all the relevant information has been found. Factors that have an influence on how people determine when to end information seeking have been discussed by e.g. Berryman (2006). Problems with retrieving information might relate to version management issues, where it is hard or impossible for designers to verify that they have found the latest updated version of a document or specification. Chowdhury and Gibb (2009) discuss different types of uncertainty associated with information seeking and retrieval, and state that uncertainty is a significant factor in the search process. Sharing is complicated by the need to spread information to several stakeholders across departments and across engineering disciplines, calling for the use of different systems integration techniques of sharing and collaboration (Prasad 1999). One proposed way to facilitate this need is formally assigned roles in an organization, which are suggested to be an effective facilitator to support information sharing across engineering disciplines (Adamsson and Malvius 2005). Information sharing in complex product development is further made difficult by integration problems due to the use of diverse information technology (IT) and information systems (IS) (Crnkovic et al. 2001; Svensson and Malmqvist 2001). Finally, information storage is a cumbersome task since there is seldom a well-defined placeholder for information that is aligned on a system or overall project level.
As part of the research process, an exploration of the research field was performed initially to get an increased understanding of the background of efficiency problems in industry. The findings from this pre-study (see Table 3 page 27, study 1 for details on study design) functioned as input for the research questions in this thesis. The study was initiated to identify both organizational aspects (e.g. organizational roles and work procedure) and technical aspects (e.g. product complexity and IT/IS) that are important in order to support complex product development. From the study it could be stated that there is a limited understanding in the overall organization for software development needs, software being the novel technology in the context of the studied products. Designers included in the study experienced a lot of problems related to information management, which made information searching, retrieving and storing time-consuming activities. The problems regarded direct and indirect communication; via computer systems as well as human to human, for example referring to insufficient IS integration and incoherent terminology. The lack of support for exchanging information in a formalized way was identified by the researchers as one major problem, leading to the making of errors and the need to re-engineer design tasks, which demanded time-, resource- and effort-consuming activities as a result. Problems also concerned, for example, requirement specifications that were inconsistently written, allowing several levels of product abstraction in the same development phase. Designers struggled with information overload and with the need for searching documented information. This was combined with the need to search thousands of pages of text edited requirement documents. Requirements were stated as models in domain-specific IT tools (such as CATIA™ and Simulink™ for example) but handovers of requirements between different engineering disciplines were made in text documents, after which the documents were re-interpreted by the receiver of the information into models again. Designers experienced problems with configuration management and insufficient requirement management. In summary, the identified problems were to a large extent caused by issues coupled to inconsistent documentation and poor integration of information. The findings were verified by the company in workshops, and resulted, among other things, in a seminar held at the company where the importance of these issues was discussed. In all, this validation further strengthened the motivation for addressing the identified research area, which also is mirrored by previous research (Moenaert and Souder 1990; Kahn 1996; Browning et al. 2002).

1.1.1 Research questions

The need reported in literature to overcome a variety of obstacles with information management in product development led to the understanding that there is a need for companies to identify which problem areas within information management are strategic to come to terms with. The initial study led to the insight that electrical and software developments in particular experience a great need of information-related efficiency improvements. This resulted in the formulation of the following research questions (RQ), stated with the purpose of identifying important factors and strategies for efficient information management:

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2 A simulation tool running on top of Matlab™; www.mathworks.com
RQ1 What key factors are important for efficient information management in complex product development? Which ones are critical to achieve improvements in?

RQ2 How can organizations enhance and take the identified factors into account?

RQ3 What expected benefits does integrated information management entail?

1.1.2 Research scope

The scope of this research is product development. The studies originate from the R&D departments at Swedish automotive companies. Particular focus is given to electrical and software R&D departments for three major reasons:

1) Trends in the automotive industry show that the number of electrical functions is steadily growing, along with an overall increasing system complexity (Grimm 2003; Broy 2006). A multitude of different electrical systems ranging from infotainment systems to active safety systems are integrated in today’s vehicles. These systems are mainly realized in electronics and software and it is estimated that 80% of future automotive innovation will be driven by electronics, 90% of which will be software (Grimm 2003; Bernhart and Vos 2004), which indicates its importance in product development. This development has changed the automotive companies’ responsibility from mainly assembling parts obtained from suppliers to becoming a systems integrator (Pretschner et al. 2007), posing new challenges for collaboration along the product lifecycle. Integration of software into a more mature mechanical product development tradition is considered an interesting and beneficial research area to investigate and develop, since it still poses challenges to industry.

2) Electrical and software R&D departments experience a critical need to integrate information from other engineering disciplines, since they need to consider interface dependencies to other technology, e.g. due to the existence of software functionality distributed over several subsystems. In other words, there is an increased need in these departments to regard and interchange information from several engineering disciplines and IS.

3) There is a practical implication in restricting the research scope to electrical and software R&D departments, since this boundary is naturally reflected as a common organizational structure, and one that keeps electrical and software development physically separated from other areas, e.g. mechanical development.

The focus of this thesis is on information management in a product development context. There are several research motivations for focusing on information management. Information management improvements are considered an important way to make product development more efficient and less time-consuming. This is supported by Sellgren and Hakelius (1996), for example, who state that information management is a vital component for the successful integration of engineering activities with efficiency goals. Also, research shows that
approximately one third of the work hours of product development are spent on information
managing activities (Saaksvuori and Immonen 2004). Nambisan (2003), considering the
applicability of IS theories and models in a product development context, states that the IS field
can contribute as a reference discipline when addressing several problems in product
development research.

The scope extends to include information management within one organization with focus on
information exchange between engineering disciplines, and management of information systems.
To define the information management scope further, it is necessary to say a couple of words
about the term information. The “Information hierarchy” (Figure 3), first mentioned in
information science by Cleveland (1982), distinguishes between data, information, knowledge
and wisdom. Raw Data, at the bottom of the pyramid, is without context or meaning. Then
follows the Information Level, which is considered in depth in this thesis. Contrary to data,
information holds contextual meaning. The next refinement level in the pyramid is Knowledge
that encompasses relationships and rules, and is used to solve problems. At the top level of the
pyramid Wisdom resides, involving skills such as understanding of facts, evaluation, uncovering
underlying assumptions and learning from experience.

![Figure 3 Information pyramid (Cleveland 1982)](image)

Information according to Singer (1996) is defined as data that has been processed. In order to
accomplish this processing of data and information, organizations need a logistical system (Daft
and Huber 1987). Daft and Huber also identify the organizational need of a second, interpretative
system used for knowledge transfer to enable the appropriate perception of data and information
and turn it into knowledge. This thesis does not comprise perception and interpretation issues
relating to the latter system (which turns information into knowledge), but rather focuses on the
way information is processed and managed in the logistical system. Product-related information
is the key consideration here, e.g. design models and requirements that are used in the product
development process, and refined throughout the life cycle. In this thesis, information is defined
in accordance with the overall use of the concept within the new product development field, as
suggested by Frishammar (2005): “information is value added data, a body of facts and
knowledge to be applied to the solution of problems or to support decisions”.

This research makes an attempt to take on a systems thinking perspective to information
management in product development. The research approach includes an implicit understanding
of the need for information produced at early stages of development to be used in later lifecycle
stages. Even though other organizational functions, such as e.g. manufacturing and after market
departments have not been included in the research scope, an attempt has still been made to
apply an information lifecycle perspective. The researcher has consistently observed the
information transfer to, within and from the R&D department, reflecting on the potential
implications for other stakeholders throughout the lifecycle, and considering feedback loops back
to the R&D department with information that has been refined at later stages. Furthermore, an
attempt has been made to apply different perspectives on information management, such as
operative and strategic perspectives.

The aim of the research has been to incorporate both technical and organizational dimensions
into these perspectives. A simple emphasis e.g. on IT alone does not necessarily lead to optimal
information use, as information overload is a common problem in organizations (Singer 1996).
In order to comprehend complex product development it is essential to consider different
dimensions such as people, processes, technology and organization (Sage and Lynch 1998;
Nambisan and Wilemon 2000; Eppinger and Salminen 2001).
2 THEORETICAL FRAME OF REFERENCE

The bulk of the theoretical frame of reference is built from two main areas of which an orientation is made: perspectives used in product development and information management research. The aim is to present a general conception about these areas including relevant sub-areas that have contributed to the overall understanding and grasping of the research field. Initially, some integration aspects of product development are considered.

The significance of organizational integration to achieve performance in product development is addressed by several researchers (e.g. Kahn 2001; Faems et al. 2005; Sherman et al. 2005). Faems et al (2005) report on a positive relationship between inter-organizational collaboration with company networks (involving e.g. suppliers) and innovative performance, while studying a smaller element of the organization, Kahn (1996) states that inter-departmental integration positively influence performance. Overall, there is a consensus in literature about the need for organizational integration to obtain efficient product development. Much research attention within organizational integration has been devoted to the interfaces between marketing, manufacturing and R&D (Adamsson 2007). Experts from different engineering disciplines within a company (and from external organizations) are typically involved in the development of complex products, not necessarily implying grouping into different functional departments. Cross-functional refers to the interaction and collaboration between two or more organizational functions, whereas interdisciplinary integration is defined as the state and quality of interaction and collaboration activities that involve two or more engineering disciplines (Adamsson 2007). Adamsson concludes that there is a need for a shift in research focus in complex product development from cross-functional to interdisciplinary integration.

Focus in this thesis when it comes to technology integration is on the use and integration of the different information systems (IS) that are needed in product development (This is further elaborated in Chapter Management of information systems). However, technology integration also refers to technical interfaces in product modules that need to interact and fit in with one another – for example the integration between components, assemblies and sub-systems, where all internal and external interfaces, data flows and control structures, and the interaction with external systems need to be managed (Stevens et al. 1998). As the different systems/sub-systems/components are integrated one main goal is to ensure that the interfaces are successfully integrated (Haskins and Striegel 2006). Typically, in the case of an original equipment manufacturer (OEM), such as an automotive company the technical integration is further
complicated by the need to integrate different instances of technical interfaces from components or sub-systems to systems acquired by external suppliers (Stock and Tatikonda 2004; 2006). Aspects of technology integration when it comes to products are not studied explicitly in this research, but are mentioned since it is important to be conscious of their existence when addressing issues in complex product development.

2.1 Human interaction and collaboration

A complex product is the result of a collaborative design process, which makes it important to capture dependencies arising from such collaborations and consider relationships to existing designs (Majumder et al. 1995). The nature of complex products - with their demand of systems integration and a need for personnel interactions - requires the existence of good communication channels (Blanchard and Fabrycky 1998). The development of distributed systems complicates communication, which gives rise to unstable and frequently changing requirements (Pretschner et al. 2007). Most communication between involved stakeholders in product development is organized via a requirements document that often is not sufficient nor precise (Broy et al. 2007). This is compounded by the fact that designers as well as suppliers often only have a view limited to their own sub-system and that they lack the big picture of how the systems interact with other parts of the system (Almefelt et al. 2006).

The logic and rationale behind design-related decisions may differ between software-related issues and issues related to mechanical aspects of the product. In companies where new technology plays a strategic role in the product function, organizational issues such as structures, processes and cultural differences form obstacles (Karlsson and Lovén 2005). Karlsson and Lovén state that cultural aspects are specifically important in companies with short experience of software integration in hardware development. Different engineering disciplines within R&D perceive technology differently, leading to electrical engineers trying to find electrical solutions to problems, whereas software engineers look for computer solutions (CIMdata 2006a). The existence of different “thought worlds” or self-contained societies within the same organization, each consisting with their own knowledge base is one example of an organizational barrier to integration (Griffin and Hauser 1996; Karlsson and Lovén 2005). As a consequence language barriers (use of different terminology and nomenclature) may arise, with the development of specific technical jargon, often allocating different meanings to similar terms (e.g. system, function and component) (Buur 1990; Bradley 1997). As a consequence, miscommunication between - and even within - organizational functions and inconsistent understanding of the problem may arise, as simplified illustrated in Figure 4.
Thus, interdisciplinary integration tackles the integration of people that need to communicate and exchange information in spite of the existence of different cultural and/or engineering background and level of initial problem understanding. The standpoint taken in this research is that differences in perception and use of terminology will remain part of the organizational culture and need to be allowed to exist. Rather than focusing on the absence or presence of these barriers, focus should be on how they are overcome and they should be dealt with explicitly to improve innovation in large firms (Dougherty 1992).

2.2 Product Development Perspectives

The need for processes in design work has been long known. To a large extent, development work has been studied as a linear process with sequential dependencies between tasks. This is reflected in several product development processes, which are based on chronological phases that describe a consecutive sequence of stages (Pahl and Beitz 1988; Ullman 1997; Ulrich and Eppinger 2007). The need for improved coordination and integration between organizational functions, projects, and process stages has laid the foundation for a new approach in research, focusing on the collaborative aspects of product development (e.g. Wheelwright and Clark 1992; Utterback 1994; Cusumano and Nobeoka 1998). With this perspective the product development process is described as simultaneous activities to better meet the need in industry for iterative work and flexibility in the design process. One appurtenant domain that grew in significance during the 1990’s (Gerwin and Barrowman 2002) is integrated product development, which is described more in detail in the Chapter Integrated product development.
In their classic article from 1995, Brown and Eisenhardt (1995) categorize product development literature into three streams of research including rational plan, communication web and disciplined problem-solving. It is suggested that this research can be mapped into the second stream, still it somewhat encompasses all three approaches. This is in line with the suggestion made by Brown and Eisenhardt that the three streams provide basis for an integrative model due to overlapping and complementary foci. For the communication web stream work concerns the effects of communication on project performance, and includes information-processing aspects of product development. The underlying understanding is that communication among project team members and with outsiders stimulates the performance of development teams. Of special relevance to this thesis is the by Brown and Eisenhardt suggested sub-stream “internal communication” among team members that is characterized by high, experiential, iterative and non-routine communication.

By tradition, designers belonging to different engineering disciplines use diverse processes and approaches when developing mechanical, electrical or software components. This is reflected by the existence of domain-specific and rather independent research areas within product development literature. One article written by Nambisan and Wilemon (2000) that is addressing these research domain-foci, is of particular relevance to this research since it highlights differences and similarities between new product development and software development. A divergence in research focus between the two research domains are reported on, concluding that technology-process integration is a primary focus of software development emphasizing structured processes and the use of technologies to speed up product development processes, while people-process integration reflects key research areas of new product development including a primary focus on the impact of people and their management of the development process (Figure 5). The authors conclude the potential for the two research domains to learn from each other by addressing several important product development challenges. No explicit attempt is made in this research to address knowledge sharing between mechanical and electrical and software development but an understanding of the underlying differences in research and practice emphasis reported by Nambisan and Wilemon is regarded important knowledge when undertaking this research. The importance of integrating foci from different domains is also made explicit by their study.

Two specific approaches are used as the framework for product development methodologies in this thesis, since they both encompass systems integration aspects of development: integrated product development influenced by the European mechanical design tradition; and systems engineering rooted in American defense industry. Both perspectives include technical and organizational dimensions of product development but with slightly different foci: integrated product development has a stronger focus on managerial aspects, while a core element of systems engineering is technical coordination (Stevens et al. 1998).
2.2.1 Integrated Product Development

Integrated product development as a domain has evolved from traditional engineering design methodology that roots back to the mid 1960s (Blessing 1996). Integrated product development was first named and explained in 1976 (Olsson), after which the concept was further developed by Andreasen and Hein (1987) who pointed out the importance of considering work aspects in development in addition to mere product function. Integrated product development combines engineering and management perspectives of product development and should be seen as a cross-domain perspective. Characteristic for this perspective in comparison to other approaches to product development is the simultaneous consideration of several issues related to the development of a product. This encompasses cross-functional teamwork – meaning the interaction and collaboration between organizational functions (marketing, R&D and manufacturing etc) – where development occurs through overlapping and parallel activities focusing on aspects related to both process and people. Integrated product development is also typically characterized by the use of product development processes, support methods and consideration of customer needs. Norell (1999) defines integrated product development as an approach based on a holistic view including products, processes and individuals. The co-existence of work procedures, methods and tools, and information management is necessary to accomplish integrated product development (Norell 1992). Considering the relationship between these factors, Norell goes on to highlight that the benefit of relevant methods and tool and information management are both dependent on the existence of work procedures, leadership and organization that support cross-functional and interdisciplinary collaboration, a concept which underlies this thesis when focusing on information management related issues in order to achieve integration (Figure 6). Gerwin and Barrowman (2002) suggest a similar definition to
integrated product development, defined as “a managerial approach for improving new product development performance (e.g., development time), which occurs in part through the overlap (partially or completely parallel execution) and the interaction (exchange of information) of certain activities in the new product development process”. Gerwin and Barrowman also narrow the product development scope identified by Brown and Eisenhardt (1995) further, suggesting three main approaches in research to integrated product development: an organizational design approach; information-processing approach; and the application of manufacturing principles to product development. From an information-processing approach, integrated product development is regarded as a problem-solving process that enables an organization to transform information along the design process, starting in market opportunities and technological possibilities into a product design solution.

![Figure 6 Integrated product development based on Norell (1992). As illustrated in the figure, focus in this thesis is on information management, though an attempt has been made to consider all three aspects.]

### 2.2.2 Systems Engineering

Systems engineering has a more formalistic approach to product development than the integrated product development domain. The modern origins of systems engineering can be traced back to the 1930’s (INCOSE 2007). The domain grew in importance with the rapidly emerging aerospace industry, and still has its strongest hold in the US. Systems engineering includes both technical processes and management processes and is a key approach to manage complexity and the development of large systems (INCOSE 2007). From a technical perspective this implies that systems and sub-systems with different technical content are viewed as an integrated part of an overall product, integration aspects on development (including e.g. interface controls, system of interest analyses, and configuration management) being typical of this domain. The managerial aspects of systems engineering include an understanding that systems development activities must be applied throughout the life cycle on: the development system; manufacturing system; deployment system; training system; maintenance system; refinement system; and retirement system (Farr and Buede 2003). Systems engineering is different from specialist disciplines such
as mechanical or electrical engineering in that it provides the framework of all other disciplines and involves every discipline taking part in a project and every team member, not just part of some of the developmental and organizational levels (Stevens et al. 1998).

Loureiro et al. (2004) give a broad overview of the evolvement in the automotive industry stating that development started off from a component-based focus. Once life cycle process requirements and interconnections between components needed to be taken into consideration, a better understanding of the contribution of each product and/or process component to the whole was required. They argue that however, in practice there still is a strong focus on the product elements of a system. They propose a framework that applies the systems engineering approach within the context of integrated development, enabling the whole system to be considered as an integration of product, processes, and organization elements. Thus, in a similar way as Nambisan and Wilemon (2000) (discussed previously), this is another example of an approach that combines two different product development perspectives. Applying this total view approach for an integrated automotive development leads according to Loureiro et al. to the suggested benefit that companies early on in the process are able to investigate the interactions between requirements and attributes not only of the product, but also of its life cycle processes and their associated organizations.

The system lifecycle process ISO/IEC 15288 (2002) is designed for systems development. It is an international standard that constitutes a generic process description that identifies four main process groups to support systems engineering: technical; project; enterprise; and agreement processes. Different disciplines are not considered separately, and a multidisciplinary approach is integrated in the applied processes, which makes ISO/IEC 15288 relevant in particular for complex product development. One process example is the V-model that is used in systems engineering as support to achieve an integrated perspective. The V-model is specifically relevant to this work since tailored V-model based processes were applied as product development process in the studied companies. The V-model adapted for systems engineering is based on the VDI 2206 standard first released in 1993 as a design methodology for mechatronic systems (VDI 2206). Rather than exemplifying a process with defined gates and activities, the V-model consists of design guidelines that advocate an iterative approach with continuous verification and validation of system requirements, both on sub-system and overall system levels. In the left leg of the V-model, requirements are refined through different levels of system and sub-system design. The right leg concerns systems integration of the domain-specific designs (Figure 7). Haskins and Striegel (2006) take the V-model as starting point for discussion on two different integration challenges of complex systems: obtaining a clear understanding of validation and verification activities at all levels of development; and controlling of key interfaces between systems, sub-systems and components. Both these aspects are further suggested by the authors as key aspects to having a successful integration of complex systems.
One approach that has its basis in systems engineering ideas is systems thinking that emerged due to a growing awareness of the importance to examine and understand complex entities composed of multiple elements in a holistic manner. For example, in systems thinking an organization should also be considered a system composed of system elements and relationships that must be life cycle managed (Lawson 2006). The main focus of systems thinking is to utilize a holistic perspective to understand the dynamics of interaction amongst multiple systems during their operation, suggesting that underlying problems and opportunities can be identified via this perspective. “Through systems thinking organizations and their enterprises can learn to identify system problems and opportunities and to determine the need for, as well as to evaluate the potential effect of, system changes” (Lawson 2006 p. 4). Lawson suggests that one reason for chasing problem solutions based on the consideration of one element at a time (such as inefficient tools or methods or inadequate processes) quite often has to do with having limited perspectives. In this thesis, systems thinking is synonymous with approaching the complex interrelationships between systems in terms of hardware, software and people with a holistic view.
2.3 Information Management

Information management refers to the overall integration of: management activities in all units; the availability of data in a database management system; and the most appropriate information technologies for delivery (Singer 1996). It is suggested by Davenport (1993) that the term information management should put equal weight on the patterns and valuation of information usage, as on the systems and technology that enable usage. Evgeniou and Cartwright (2005) discuss barriers to information management and pitfalls that organizations commonly fall into. They identify three fundamental categories of barriers: some of the pitfalls are due to behavioral biases; others are due to basic misunderstandings of key characteristics of information management projects; while others are due to organizational factors.

Traditionally, the research area of information management has had a strong focus on product development (Andersson 2005). Information management and information communication technology are seen as important focus areas for performance in product development (Leenders and Wierenga 2002; Haque and Moore 2004). Several researchers have addressed the role that information plays in product development (e.g. Zahay et al. 2004; Frishammar 2005; Loch and Terwiesch 2005; Howard et al. 2006). Overall, the ability to acquire and disseminate information is considered important to ensure efficiency in product development organizations. However, Hallin et al. (2003) argue that research presented on the topic of complex products is insufficient regarding product information management, indicating a greater need for studying information management aspects for complex product development.

Information in complex development settings acts as the conjunction that enables interaction between technology, organizations and the environment (Sage and Lynch 1998). Davenport (Davenport 1993) stresses the value of thinking about information as a process entity and discusses four different roles of information in a process. Firstly, information is regarded as a supporting tool to make processes more efficient and effective, usable for process monitoring, integration and customization. Secondly and thirdly, Davenport distinguishes between two types of information-oriented processes: those designated to aid management decisions and activities; and those with operational objectives. The fourth role is the focus on the management of the information itself within a process. Here, the structuring of organizational units that are responsible for management of information is regarded as a key aspect.

Zahay et al. (2004) address the issue of how to catalogue information into specific types, sources, and forms, and identify what types, sources, and forms are needed during the appropriate stages of the product development process to further enhance success and attain organizational goals. They state that there is a lack of a full picture of information usage throughout the entire development process, and that the need for information varies throughout the process, intensifying in early and late stages. Table 1 lists examples of differences between ideal and real management of information in product development.
Table 1 Reality versus the ideal in managing information for new product development (Zahay et al. 2004).

<table>
<thead>
<tr>
<th>Knowledge management capability</th>
<th>“Ideal” result</th>
<th>Reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information management dimensions</td>
<td>Company recognizes sources and forms of information and where in process each is used</td>
<td>No formal process for integrating sources and forms of data into NPD, no way to measure success</td>
</tr>
<tr>
<td>Organizational structure</td>
<td>Companies organized to integrate information, the highest form of knowledge management</td>
<td>Three different types of structures, most companies still project and function centered</td>
</tr>
<tr>
<td>Data sources</td>
<td>Analytical tools used to integrate information throughout the NPD process</td>
<td>Tools used for project management, cannot handle text documents well, many e-mails, notebooks still used</td>
</tr>
<tr>
<td>Data types</td>
<td>Customer information and wants and needs primary, some competitive</td>
<td>Eight different types of information used in NPD process from across the organization</td>
</tr>
<tr>
<td>Information about wants and needs</td>
<td>Wants and needs information fully integrated into process</td>
<td>Qualitative data difficult to capture and manage within and across projects</td>
</tr>
<tr>
<td>Information about customer</td>
<td>Information about customer used first, wants and needs second in beginning stages</td>
<td>Not everyone using customer information up front. Example, customer satisfaction information at end</td>
</tr>
</tbody>
</table>

Complex product development is suggested to be a requirements-driven process (Almefelt and Andersson 2003). Given that most requirements are textual and document-based, and since documents are weak at showing relationships (Stevens et al. 1998), one effect of this condition might be that designers are not provided with a true reflection on the complex and dynamic nature of inter-relations between information objects. This suggests that document centric requirements mainly provides a hierarchy for the requirements, often in accordance with the heading structure, without giving any support for internal relationships between requirements. Stevens et al. (1998) propose that focus is made on how to write individual requirements that are consistent, justified, clear, unambiguous and verifiable, instead of focus effort on the intrinsic quality of the information. Documents become more useful if they are structured in a consistent way so that they can be easier retrieved and accessed more effectively with aspect to contents (Liu et al. 2008). Both the accuracy in which requirements are written and the structuring of documents are acknowledged as important issues. However, document-oriented development may draw away attention from management of the overall perspective on how the requirements interact.

2.3.1 Model-based development

The use of models as a part of requirements has for long been investigated in research. Model-based development (MBD) is frequently discussed in literature as support to manage complexity. In such an approach, the models thus form the basis for the interactions between the teams of the organization, information flow within and between development phases, and for the design decisions made. For convenience, the term MBD is here used as a generic term for any systems
or software engineering methodology that is based on models and modeling. However, several other terms are used – e.g. model-based engineering (MBE), model-driven development (MDD), model-based systems engineering (MBSE). The most relevant variant in this context is MBSE, which is a formalized modeling approach for systems development suitable to support activities such as requirements analysis, design, and verification and validation (Sellgren et al. 2009). MBSE is proposed to result in systems design integration and reuse of system artifacts (Friedenthal et al. 2008). Preferably, MBD is based on abstract representations of a real or imagined system with predefined and documented syntax and semantics, supported by tools (Larses 2005). However, in practice the existence of support tools that are integrated company-wide, with alignment in process and semantics, are rarely the case.

Different graphical representations (such as functional flow block diagrams, behavior diagrams, N2 charts and reliability models) are frequently used in complex product development. These representations are closely related to each other in the context of data and functional control capabilities (Long 2002), leading to a need to exchange and relate the information captured in these models. Wikander et al. (2001) discuss requirements on model content from a multidisciplinary development perspective, and ways to allow the use of discipline-specific models whilst maintaining links between different representations. In order to achieve this, a thorough understanding of cross-domain effects and corresponding suitable abstractions needs to be obtained (for example referring to how a decision in embedded systems design will impact vehicle control systems performance) (Törngren et al. 2006).

Different types of views need to be represented in MBD. Different design views are used within different engineering disciplines; Roos (2007) addresses the existence of multiple modeling views within the engineering domain, and points out the need for interchangeability of models between domain-specific design tools; Then there is the issue of multiple views within one discipline and views that reflect the product architecture. For example, a well known view model for software development is the 4+1 view model of software architecture (Kruchten 1995), which includes a logical view, an implementation view, a process view, a deployment view, and an integrating use-case view. Thus, when addressing issues in MBD the understanding of multiple views and their integration is stated as one key issue to consider for successful use and adaptation (Törngren et al. 2009).

The Unified Modeling Language (UML™)3 is the most widely used standard for modeling and building software. To promote the adoption of UML-based concepts, beyond software communities, variants of the UML have been and are being introduced, for example the Systems Modeling Language (SysML™)4 for systems engineering. SysML is a derivative of the UML that introduces textual requirements within a graphical modeling language, thus connecting textual requirements with models, and also providing traceability between requirements and with

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3 www.omg.org
4 www.omg.org
respect to design elements. Bridges between SysML and simulation tools are being investigated, for example to generate test cases directly from requirements (Schamai et al. 2009).

One suggested approach for facilitating information exchange is the use of standards. The most well known information standard in the context of product development is ISO 10303, more commonly referred to as STEP, the standard for the exchange of product model data. STEP is an ongoing standardization attempt to provide industry with information models defining standard relationships between information objects. Stevens et al. (1998) compare an information model with a schema that states how the information is organized, with its inter-relationships (showing relationships between information objects) and dynamics. One related part of the standard is the application protocol (AP) 233 which is adapted for systems engineering data representation. One expected benefit with standardized information models is the possibility to manage extensive information exchange between different databases.

2.3.2 Management of information systems

Information technology (IT) has had a rapid infusion in organizations, and today’s organizations are dependent on the existence of tool support to manage information in product development. Nambisan (2003) states that information and knowledge management is one out of four dimensions of product development that are identified as affected in particular by the use of IT/IS (process management, project management, and collaboration and communication being the other three domains). According to Wainwright and Waring (2000) one concern of this evolvement is that “the pace of technological innovation and ‘push’ has outstripped the business or organizational ‘pull’”. Hence, there is a need to look into management aspects of IS.

Designers need the freedom to create and utilize information in their own specific expert tools, disciplinary support design tools and/or separate databases. However, information created in domain-specific IT tools relies heavily on the possibility to manage and share this information throughout an organization. IS offer interfaces to IT tools, enabling communication and management of product data across an organization, as well as increased information availability and transparency. Examples of IS are Product development management (PDM) systems and Software configuration management (SCM) systems. PDM systems offer common IS support, and SCM systems similarly support software development. PDM systems help to create, store and retrieve product data, but they also integrate and manage processes, applications and information (Sellgren 1999). Integration problems between PDM and SCM systems are caused by differences in visions, assumptions and underlying technologies (Crnkovic et al. 2003). Product lifecycle management (PLM) systems are an attempt to integrate the different systems used in product development in order to find IS support that works for the entire business (Saaksvuori and Immonen 2004). Company-wide IS, such as PLM systems have been proposed by Saaksvuori and Immonen as a means to reduce non-value-adding work. PLM systems have been of particular research focus since they are intended to support management of information from different engineering disciplines. In addition to the demand for technology integration,
PLM also needs attention to organizational integration aspects and should be regarded as a strategic business approach that support integration of people, processes, business systems and information. Ideally, PLM provides a product information backbone, the infrastructure to integrate the design teams, where all stakeholders may use reliable information for simulating the design of the product or processes (CIMdata 2006a). But challenges still exist in terms of IS integration due to the different traditions within a company and the state of the legacy systems (CIMdata 2006b).

Due to the large number of different IT/IS that typically exist in a company, attempts are made to integrate the different IS used in product development in order to find IS support that works for the entire business. Extensive amount of research has been made on IS integrated solutions (e.g. Crnkovic et al. 2003; Burr et al. 2005; El-khoury 2006). In practice, though, it is difficult to obtain this integration. In addition to challenges with underlying technologies, challenges in terms of achieving integration between IS also exist due to differences in e.g. visions and assumptions among users (Crnkovic et al. 2003). Waring and Wainwright (2000) state that integration of IS has impact on individuals, functions, the design of work processes, the process of technology adoption, strategy formulation, organizational design and behavior. They further point out the unrealistic goals and expectations with IS integrated solutions, and argue that the complexity of what is being undertaken when initiating attempts on company-wide IS integration is not fully appreciated by the implementers. Wainwright and Waring (2004) conclude that greater emphasis must be placed on organizational aspects when implementing integrated IS in order to balance the prevailing focus in industry on technical and strategic issues. The combination of technology-intensive products and large organizations, where information is used by many different stakeholders and applications, is way beyond the scope of typical IS integrated solutions.

When considering challenges with IS, it is important to remember that only the IS that actually are being used adds value to the company as stated by Abrahamsson (2004). This is in line with Dhillon (2005) who suggests that the true benefits with IS implementations reside within the organizational activities. Successful IS adaptation and how IS is spread between users rely on more than the mere issue of whether or not there is user access to the technology itself. Presumptive users have to experience a need for IS if they are to become motivated users (Lindahl 2005). Beliefs and attitudes are considered important aspects of technology adaptation (Agarwal and Prasad 1999). Management need to relate to differences with perceived benefits with IS, for designers to be properly motivated to adapt IS (Bergsjö and Malvius 2006).

IS are used for managing information, but for systems to be successful they need to be built on an understanding of how engineers work (Lowe et al. 2004). In order for IS to become easily accepted by users, it must fit into a company’s existing development process and be integrated with tools that are already in use (Beskow 2000). Unless IS is embedded into the product development process risks are that the new technology will not be used and its benefits will not be realized (Barczak et al. 2007). Barczak et al. present findings that suggest that IS usage in
product development provides far more value to firms than previously thought, and provides evidence to support greater investments in IS for product development efforts. The understanding that both organizational and technical pre-requisites in organizations need to be considered in IS implementations is reflected in literature. Possibilities and strategies with IS implementations, including e.g. the need for process alignment and organizational change are considered in related research when recommending IS roadmaps and introduction plans (Pikosz et al. 1997; Garetti and Terzi 2005; Rangan et al. 2005; Batenburg et al. 2006). However, little focus is made on the interaction between different factors that affect an IS implementation, and increased research efforts are suggested on the topic (Waring and Wainwright 2000).

2.4 Concluding remarks about the theoretical frame of reference

The presentation made in this framework has had the intention to highlight areas that are of special interest to integrated information management. Several areas have been considered, while others have been omitted from the discussion. Taking on an integration approach to information management is in itself a difficult task, including the need to include “all” organizational and technical factors. One way to delimit the framework has been by not including social structures and structures of a more “definite” character such as e.g. organizational structure, marketing aspects, ontology or product architectures, since they are regarded as being part of the social or political establishment, or regarded as a necessary (not optional) part of reality – company external or internal – that organizations face. Rather than trying to address possible adaption to such structures, the aim has been to present areas that are believed to be object of change if needed. It is the author’s firm belief that the level of integration and complexity of automobile functionality and the interactions between these components pose the need for a combination of different theoretical domains such as e.g. integrated product development and systems engineering, as stated by Loureiro et al. (2004). Research, or rather lack on research in the area, also indicates a need to focus on integration on an interdisciplinary organizational level as suggested by Adamsson (2007). As reported, a lot of research has been done on tool requirements for obtaining integrated views in development. Further investigation is needed on how to address and integrate different views from a systems thinking perspective to offer practical implications for managerial support. It is also important to gain further insights in designers’ mind-set – including e.g. needs and expectations – related to information management in complex product development. In addition, increased knowledge and consideration on the user attitude with IS implementations is regarded as essential. This is true in particular for implementations of large-scale, company-wide IS as in the case of complex product development settings.
3 RESEARCH APPROACH

The scientific research paradigm lays the foundation for the entire research project and guides the researcher both on an epistemological and ontological level (Guba and Lincoln 2000). Thus, when addressing a research problem, it is important for the researcher to decide what kind of scientific approach to take. According to Morgan and Smircich (1980) this is more important than primarily choosing research methodology. In this research, the consideration of scientific position is considered an important first step to take. Of the four competing paradigms that are discussed by Guba and Lincoln (2000), shown in Table 2, this research takes its standpoint from constructivism. Rather than relying on a special set of techniques, research according to constructivism is considered a system of pre-assumptions and mind patterns that are commonly acknowledged within the scientific area. Ontology (that is, understanding of the world) is based on these adapted structures. According to constructivism, the nature of research is regarded as a dependency on socially and experientially based values making it impossible for the personal preconceptions of a researcher to deflect from the object of investigation. It is a question of looking upon the studied problem as open, where the intention is to examine the problem from a holistic view closely interacting with its context. When it comes to epistemology (or theory of knowledge) constructivists maintain that scientific knowledge is subjective and created by interaction between people. Thus, the understanding is that it is not possible to separate “knowledge from the knower” (Alvesson and Sköldberg 1994), which also is the assumption taken in this research.

Table 2 Ontological and epistemological standpoints between four competitive paradigms that together form a continuum; positivism, post positivism, critical theories and constructivism (Guba and Lincoln 2000).

<table>
<thead>
<tr>
<th></th>
<th>POSITIVISM</th>
<th>POST POSITIVISM</th>
<th>CRITICAL THEORIES</th>
<th>CONSTRUCTIVISM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ONTOLOGY</strong></td>
<td>Realism</td>
<td>Critical realism</td>
<td>Common structures</td>
<td>Relativism</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Construction of reality</td>
</tr>
<tr>
<td><strong>EPISTEMOLOGY</strong></td>
<td>Possible to decide how things really are</td>
<td>Approximation possible, but not absolute knowing</td>
<td>Knowledge is subjective</td>
<td>Knowledge is created in the interaction between researcher and respondent</td>
</tr>
</tbody>
</table>

25
Once the scientific approach was regarded, the choice of research methodology in this research has been guided by the nature of the research questions. The standpoint taken has been that the research questions control the need for a certain research method or methods. Depending on the type of research question, different sets of methods have been used, consisting of both qualitative and quantitative methods.

3.1 Research process

In the same way that the product development process is an iterative one, the research process involves different activity phases and feedback loops. According to Alvesson and Sköldberg (1994) case study-based research often uses an abductive approach, which combines deductive and inductive reasoning, and alternates between reality and theory, as illustrated in Figure 8. As such, the researcher has followed the principles of an abductive approach, iterating between empirical data collection and theory development. Initially, four empirical case studies were performed during 2004-2006. The overall findings from these studies resulted in the development of a conceptual theoretical model that was tested in 2007 and then refined further. Although the overall research process matches an abductive approach, inductive and deductive approaches have been applied in the individual studies. Each performed case study and adherent empirical data collection was followed by data analysis and a literature review, making up smaller iterative loops within each case study. However, with the exception of the concluding synthesis in Phase II, no major literature study was performed during the data collection. Rather, the literature reviews were restricted to specific sub-areas within the overall research scope, and focus in the analyses was made on the empirical findings based on individual case studies. The overall work can be divided into two major phases, explained in detail in the following section.

![Figure 8 Relationship between reality and theory and some central definitions (Patel & Davidson, 2003).](image-url)
3.1.1 Phase I – a qualitative approach

Since the nature of the research was initially explorative and descriptive, a qualitative research approach was taken in Phase I. Within Phase I an inductive approach was mainly applied that helped to develop preliminary theories based on the empirical data collected from the case studies. The empirical-based findings are related to the specific study context, although this does not exclude relevancy in similar contexts or applicability for other areas.

In total, the first research phase consisted of four individual case studies. The studies were either explorative or descriptive and thus the interview method was chosen as a proper means to answer the question “why?” (Kvale 1996). Lawson (2006) suggests that the 5 why-technique (Senge et al. 1994) can be applied in systems thinking as method to try to grasp the core issues and reasons for a circumstance, which has been part of the overall intention in this research. All of the interviews were semi-structured (Lantz 1993) and used, to different extents, interview guides designed to cover particular areas of interest for the specific study. The interviews were conducted, typed and analyzed by the researcher(s). In Table 3 an overview of the performed studies in Phase I is presented.

Table 3 Overview of conducted research studies in Phase I.

<table>
<thead>
<tr>
<th>Study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>To identify common problem areas causing inefficiency</td>
<td>To study the implementation process of model-based development</td>
<td>To identify designer needs with information management</td>
<td>To perceive designer and management perspectives on information management</td>
</tr>
<tr>
<td><strong>Research model</strong></td>
<td>Inductive</td>
<td>Inductive</td>
<td>Inductive</td>
<td>Inductive</td>
</tr>
<tr>
<td>Exploratory</td>
<td>Descriptive</td>
<td>Descriptive</td>
<td>Descriptive</td>
<td></td>
</tr>
<tr>
<td><strong>Data collection</strong></td>
<td>15 interviews</td>
<td>Project documentation 11 interviews</td>
<td>15 interviews</td>
<td>27 interviews</td>
</tr>
<tr>
<td><strong>Interviewees</strong></td>
<td>Designers, managers</td>
<td>IS suppliers, middle managers, designers</td>
<td>Designers</td>
<td>Top and middle managers, designers</td>
</tr>
<tr>
<td><strong>Studied industry and departments</strong></td>
<td>Truck company Electrical and software</td>
<td>Automotive company Electrical and software</td>
<td>Automotive company Mechanical, electrical and software</td>
<td>Automotive company Mechanical, electrical and software</td>
</tr>
<tr>
<td><strong>Publications</strong></td>
<td>(Adamsson and Malvius 2005)</td>
<td>(Malvius et al. 2006)</td>
<td>(Bergsjö and Malvius 2006)</td>
<td>(Malvius et al. 2007a; Malvius et al. 2007b)</td>
</tr>
<tr>
<td><strong>Reported in</strong></td>
<td>-</td>
<td>Appended paper A</td>
<td>-</td>
<td>Appended paper B</td>
</tr>
</tbody>
</table>
Figure 9 Case study designs in Phase I. The figure gives a conceptual illustration of the unit of analysis for each study as well as an image of how they relate to and overlap with each other.

**Study Design**

The key factor in selecting and making decisions about the appropriate unit of analysis is to decide what unit it is that you want to be able to say something about at the end of the evaluation (Patton 1987). All of the studies were conducted in electrical and software departments in automotive companies. However, the choice of unit of analysis for each individual study in Phase I has differed somewhat, depending on the study purpose and current situational preconditions. Figure 9 is an attempt to illustrate the unit of analysis for each study. The initial study, Study 1, was designed and carried out at a Swedish truck company, and aimed to get an increased understanding of the background of efficiency problems in industry. Exploratory research (Stebbins 2001) was conducted since at this stage of the research, a problem had not yet been clearly defined, and the intention with the study was not to draw definitive conclusions based on the study outcome. Key informants were mainly selected as sample for the interviews since they are people who are particularly knowledgeable and whose insights can prove useful in helping an observer understand and explain what is happening (Patton 1987). The three consecutive studies (2-4) were all performed at another automotive industry company. A change project performed within one company project was used as the unit of analysis for Study 2. The interviews covered 100% of the project team members, including designers, middle management
and IS supplier consultants. In this case extreme (or deviant) case sampling was made (Patton 1987). The unit of analysis for Study 3 was designers in great need of IT/IS support. The study was performed in electrical, software and mechanical departments within the company. Including interviewees from the mechanical department served as a reference object to the statements made by electrical and software designers. The study covered the relationships between designers and IT/IS, focusing on the need for and views on information management from a user perspective. Snowball or chain sampling was applied in order to locate information-rich key informants (Patton 1987). Finally, in Study 4, a similar study was conducted that included management to complement the designer and technical views.

Phase I was concluded with a licentiate thesis (Malvius 2007) that summarized the research results from the qualitative studies. The final synthesis presented in the licentiate thesis along with suggested key indicators for efficient information management, form the basis for the research performed in Phase II.

### 3.1.2 Phase II – a quantitative approach

In practice, Phase II somewhat overlapped with Phase I, since it started in parallel in November 2006. A deductive research approach was applied in Phase II, with modification of the Phase I findings into a preliminary conceptual theoretical model (presented in Paper C). Based on this model a survey was designed that was empirically tested in the beginning of 2007 to statistically verify the model’s significance and relevancy. The outcome resulted in a refined research model that includes weighted factors for efficient information management (reported in Paper C). An overview of the research study in Phase II is shown in Table 4, and the study design is described in more detail in the following section.

<table>
<thead>
<tr>
<th>Study</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>To identify measurements for efficiency in information management</td>
</tr>
<tr>
<td><strong>Research model</strong></td>
<td>Deductive</td>
</tr>
<tr>
<td><strong>Data collection</strong></td>
<td>Web-based questionnaire distributed to 419 employees Two workshops</td>
</tr>
<tr>
<td><strong>Interviewees</strong></td>
<td>Designers, managers, specialists, administrative</td>
</tr>
<tr>
<td><strong>Studied industry and departments</strong></td>
<td>Automotive company Electrical and software</td>
</tr>
<tr>
<td><strong>Time period</strong></td>
<td>Nov 2006 - May 2007</td>
</tr>
<tr>
<td><strong>Publications</strong></td>
<td>(Bergsjö and Malvius 2007; Bergsjö and Malvius 2008; Malvius et al. 2009)</td>
</tr>
<tr>
<td><strong>Reported in</strong></td>
<td>Appended papers C and D</td>
</tr>
</tbody>
</table>
Define a research problem, objectives and multivariable technique

Develop the analysis plan

Evaluate the assumptions underlying the multivariable technique

Estimate the multivariate model and assess an overall model fit

Interpret the variable(s)

Figure 10 Research process applied in Study 5, based on Hair et al (2006).

Study design

For the fifth and final study a quantitative research method was applied since the aim was to determine whether or not it was possible to define reliable index values to effect goals such as efficiency, innovation and quality coupled to information management. A research process presented by Hair et al (2006) was used as a model (Figure 10).

The preliminary conceptual theoretical model provided the foundation for the formulation of the survey questions. The questionnaire along with the preliminary model have been published in a working paper (Bergsjö and Malvius 2007). The design of the survey was developed in close collaboration with representatives of one of the partner companies that had taken part in case studies in Phase I. The developed survey was distributed at the company concerned. Data collection was carried out in January and February 2007. The overall questionnaire was sent to 419 employees at the electrical and software R&D department, including designers, management, and administrative personnel. Two different sets of analyses (described in Chapter Research analysis) were made based on the empirical data gathered from this study. The first analysis aimed at identifying relevant and important factors that have an impact on efficiency with aspect to information management (presented in detail in Paper C). The second analysis aimed at identifying groups of users with similar approach to implementations of a new information system (presented in detail in Paper D).

Concluding the second phase is a synthesis of overall research results and additional theory building, resulting in the writing of this doctoral thesis. In all, prior to the synthesis the analyses were made on individual studies, and reported in a way that fit the format of conference papers i.e. a case study description of limited extent. The synthesis has strived to include a combination of the overall results, whereas the choice of appended papers has partly been made to best fit and reflect supporting relevancy to the reasoning made in the discussion. The synthesis also entailed a comprehensive literature study. This was not experienced by the researcher as feasible to do prior to the overall synthesis due to the vast areas of studies, incorporating multiple fields.
separately. A more detailed understanding of what research fields should be studied in detail grew organically, along with the development of more mature research insights. At a certain point, when the time felt mature, individual studies formed a synergetic understanding of the studied field. The discussion presented in this thesis is a result of made synthesis.

3.1.3 Studied practice

Applied research is dependent on the possibility of gathering data from practice. This research is to a large extent empirical based as shown in the research process. Hence, involvement made by case study companies is a prerequisite for this research.

Kim and Wilemon (2003) state that product development can be especially costly and complex when the following applies:

• when a high degree of component integration is needed
• when an emerging technology is being developed and included in a new product
• when a company develops a product with a partner
• when a company develops a radical innovation
• when there is a need for involvement of many individuals and organizational functions

This situational context reflects the basis for the overall criteria that were used when identifying companies suitable for participation in research collaboration. One criterion related to company size and volume of employers suggesting that the participating company should consist of large organization, ruling out e.g. small and medium sized enterprises. The participating company also needed to have reached a certain level of complexity (high technology products, use of several processes, and diverse IT/IS environment). Finally, the company had to experience problems related to integration and collaboration issues.

The automotive industry is facing organizational and technical challenges including the need for integration of new software functionality into mature mechanical products, which makes it an ideal study object for research within complex product development. The focus on the automotive industry in this thesis is partly due to the studied companies’ interest in academia research collaboration, and partly due to an established network at the time when the research started, allowing for long-term collaboration and for a refinement of earlier research results. At the time of the initiation of the research project, companies included in the studies experienced improvement potential relating to information management issues. Like many companies involved in product data intensive development, they struggled with inefficiency in information transfer, traceability problems and difficulties with obtaining accurate version management, hence further qualifying as an interesting study object.
3.1.4 Research analysis

Analysis is necessary because data in raw form does not speak for itself (Robson 2002). The methods of analysis differed for the qualitative and quantitative studies, and also within the different qualitative studies. Qualitative analysis is guided not by hypothesis but by questions, issues and a search for patterns (Patton 1987). Two different methods of analysis have been used in the qualitative studies. In Studies 1 and 2 in Phase I, the interviews were transcribed wordily by the researcher in a text editor. Entire sections in the documents were thereafter coded, in NVivo™, with suitable key words. Halfway through the interviews in each study the first interpretations were made about how the key words could be organized into groups that referred to the same issue. The grouping was influenced by the similarity of key words and by the rate of occurrence of a key word (if e.g. a key word only occasionally had been coded and in the end did not fit into one of the resulting groups this key word was interpreted as not being a representative finding for the final result). After the initial grouping the results were confirmed against the coding of the remaining interviews. When a draft of the analysis was completed discussions on the identified groups and performed interpretations were made with other members of the research group, and occasionally with interviewees from the companies. If necessary, adjustments were made to the suggested groupings. The coding process for Studies 1 and 2 was empirically based. The data gathered from the interviews was used as main basis to achieve a nuanced comprehension of the findings. Between Studies 2 and 3 the researcher had gained deepened knowledge which enabled a firmer guidance of the topics that were addressed in the interviews. In Studies 3 and 4 the interviews were compiled in PowerPoint™ with key words and interesting citations. The coding followed the categories in the interview guidance. One motive for keeping to the categories in the analysis of the latter cases is that the interview guide considered certain pre-defined areas, restricting the answers in Studies 3 and 4 to addressing these pre-defined areas. In the case of Study 1 the study character was exploratory, allowing a divergence from the interview guide. Study 2 also allowed a broader scope than the pre-defined areas during the interviews.

The manifest (concrete) content of the interviews can be captured and treated as text, while the latent (abstract) interview content is harder to grasp due to its hidden character. Therefore, the analysis made to the written transcriptions was “confirmed” with the researcher’s overall perception from the conducted interviews that important areas had been covered in the transcriptions.

In Phase II the method of analysis followed the evaluation of assumptions according to Hair et al. (2006). Three main groups of analysis were performed when examining the data for multivariable analysis: analysis of missing data, identification of outliers, and testing the assumptions of multivariable analysis. Study 5 included two different statistical analyses: one Partial Least Square (PLS) analysis; and one cluster analysis. For the statistical analysis presented in Paper C a PLS analysis was performed, since this is considered a suitable method for satisfaction studies, being very robust (Kristensen and Eskildsen 2006). PLS analysis was used for theory confirmation as well as for identification of existence of possible relationships. In
all, the answers of 281 design engineers, managers and administrative personnel, a 67% response rate, was included in the PLS analysis. For the statistical analysis presented in Paper E the cluster analysis was performed on a chosen subset of 14 questions. A response rate of 78% was achieved for the analysis of this data set.

The synthesis in Phase II has consisted of coding and analysis of the overall findings to provide integration of the collected research results, mainly reported in publications (for reference, see List of appended papers and List of additional publications). In practice, a final study was performed consisting of an analysis of publications (which in most cases reported on findings from one study) and comparison to related literature as well as obtained experience. As case study-based findings were treated as data and were compared across the treated factors, several patterns became evident. These patterns led to the identification of what Strauss (1987) calls the 'core categories' or main themes that sum up the substance of what is going on in the data.

### 3.2 Research Quality

In any research, reliability, validity and generalizability\(^5\) are of major concern. For example, unless a measure is reliable, it cannot be valid; however reliability alone is not sufficient (Robson 2002). The reflections below consider how quality has been measured and addressed in this research in light of these three concerns.

The daring attempt to undertake a systems thinking perspective in this research has required the consideration of several perspectives on research issues, and has contributed with a multifacettetd understanding of the studied subject. Moreover, the research includes the undertaking of both qualitative and quantitative studies. This use of different perspectives and methods has been a deliberate strategy to balance the strengths and weaknesses incumbent in each instrument.

It is important to note that this work has been empirically driven. As a result, the theoretical viewpoints have been ruled by the empirical outcome from the studies. One research motive has been the identification of relevant areas for further research based on the outcome of empirically tested findings (in Studies 1 and 2). The researcher’s personal interest to attend to some of the identified questions also guided the continuation of the research. Once this positioning was made, halfway through Phase I, the active choice to use a different analysis method in Studies 3 and 4 was grounded in an intentional strategy to further align the research issues, including the adaptation of a convergent process: starting off with an open attitude, a more narrow approach followed to delimit the research field. In an overall sense it can be stated that the research approach has been successful in bridging academia and industry through close collaboration and relevancy of research findings.

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\(^5\) An alternative term used is "external validity".
3.2.1 Reliability

Traditionally, research is considered to have high reliability if the research findings can be replicated and the same results can be drawn. However, Merriam (2009) states that replication of a qualitative study will not yield the same results, and that this does not discredit the results since there can be numerous interpretations of the same data. More important than considering the replicability of the findings is the notion that qualitative research needs to determine whether the results are consistent with the data gathered or not. Lincoln and Guba (1985) introduce dependability and consistency in qualitative research, arguing that reliability is about determining that – in light of the data collected – the results make sense.

The quality of the results is dependent on the researcher’s skills in interviewing, skills that require practice. The less the degree of structure in the interview, the more difficult the performance required from the interviewer (Robson 2002). At least two researchers participated in each interview to compensate for some of the lack of previous interviewing experience prior to start of the research project.

For the reliability discussion concerning Phase II, it is argued that the research model (presented in Paper C) not should be uses in a static way. For example, the questions need adaptations according to company-specific use of terminology, or to fit individual contexts such as organizational roles or use of IT/IS. The intended use for the research model is in dynamic organizations that are subject to constant change. It is argued that the model can be transferred to become applicable to contextual settings similar to the automotive industry (i.e. technology- and knowledge-intensive product development organizations). It is important to consider maturity differences among organizations – the outcome of the model is among other things dependent on the maturity level at the studied company. If a company has realized the importance of a certain success factor, and has already accomplished improvement efforts in that area, the model will indicate this factor as relevant but also indicate other factors to be critical improvement areas.

3.2.2 Validity

Validity refers to the trustworthiness of the findings, or whether the findings are “really” about what they appear to be about (Robson 2002). For the qualitative studies, open questions were asked to allow respondents to discuss what they considered to be important, in an attempt to minimize the risk of affecting the answers. Respondents were chosen in collaboration with case company representatives as a means to ensure that the interviews included people with relevancy to the studied research issue. The number of respondents was not decided in advance. Instead, for each study the researcher awaited the occurrence of similar perceptions among the interviewees to take place, as a measure for validity, before beginning to finalize the interview study. At this point some additional interviews were made to further verify the gathered results. Respondents also reviewed the interview material to confirm its correctness. The data collection was gathered in close collaboration with more than one researcher, which suggests strengthening the validity
since this limits the negative influence of subjectivity. The results however, would have been more valid and more representative if perspectives from more engineering domains were included in the findings. For the quantitative study, the logic of the results was discussed at two separate workshops at the case study company. Prior to this, findings had also been validated with regard to the statistical construct by two independent researchers specialized in the applied methods used in the statistical analyses.

A comparison between the case study based findings and existing theory (Yin 1994) suggests that the overall findings can be said to be generally valid, being in accordance with accepted theory as well as on logical consideration.

3.2.3 Generalization of results

The possibility to generalize qualitative research results is questionable (Kvale 1994). Alvesson and Sköldberg (1994) argue that this attitude is dependent on what the epistemological standpoint is, and on the nature of the generalization. This research centers on studies in the automotive industry, but the majority of the empirical findings are collected from one car manufacturer. It can be stated that the findings as a whole are basically contextual. From a constructivistic standpoint the results should be considered in their contextual setting, but the implications may extend to similar systems development programs. Thus some tentative conclusions may be applicable to other systems engineering industries that develop complex systems or products in organizations of a similar size. The feasibility of generalizing these findings is dependent on whether or not sufficient information has been provided (Lincoln and Guba 1985). It is believed that, based on the given information about the research process, an estimate of the transferability of research findings to new contexts can be made by the reader.

The type of development organizations studied are dynamic, which influences the ability to generalize the research results. In this case, qualitative studies within one company made it possible to identify a selection of criteria that were regarded as important to further examine and measure in order to identify critical outcomes. The qualitative factors are not identical for every complex environment, nor should the research model be regarded as static.

3.3 Research Progress

Undertaking a research journey often involves tackling and unraveling issues from interfacing research topics. This is especially true for multidisciplinary research such as product development where both organizational and technical dimensions need to be considered, integrating process, people and product. Adopting an explorative approach to research also helps to strengthen this phenomenon. Interesting topics emerge that at a first glance appear to result in fruitful findings, requiring temporary in-depth analysis before approval or dismissal. Although
the incredible or unexpected findings frequently turn out to be plain and later disregarded, the very experience benefits the researcher to develop and mature within the field.

One research topic that received considerable attention throughout this research was the study of information systems (IS) implementations. The intention was to propose ways and methods to improve IS implementation projects, and to supply user-adapted implementations, whereas the real research gain in the end proved to be on an information management level rather than specifically coupled to tool supports. It is argued that the focus on IS implementations acted as a catalyst, by which knowledge emerged concerning the need for representations of different perspectives, and the necessity of balancing trade-offs in order to improve information management. It is the researcher’s firm belief that it is necessary to address fundamental demands for integrated information management to overcome implementation issues in IS.

Some of the knowledge attained during the research journey has been communicated in publications. Often these representations of research findings are condensed due to practical limitations, describing one detailed phenomenon or sub-system that is drawn from the overall system intention. This thesis is an attempt to merge diverse findings into a synthesis. Figure 11 gives an illustration of how findings and discussions on central research themes have been represented in publications throughout the PhD period. A mapping between relevance to topics – such as interdisciplinary integration, perspectives on information, measurements and model-based development (MBD) – and their relation to related research communities within product development – such as Design Society, ASME, INCOSE – is presented in the figure. The selection of appended papers has been made based on their capability to represent relevant foci to the overall research scope.

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6 Research communities are not presented per se, instead, conferences organized by these communities are listed, as well as a reference to adherent publication (the complete list is found in Chapter List of appended papers, and Chapter List of additional publications).
Figure 11 Mapping of published conference papers’ [rectangles] relation to central research themes (bubbles). Appended papers included as part of the thesis are highlighted.
4 SUMMARY OF APPENDED PAPERS

A summary of the appended papers (referred to as Paper A-E for short) is presented in the following section to give a short description of research findings. Paper A shows the origin of the research, based on a research project addressing model-based development, and is added to give a starting point for the reader. Paper B offers insights on different stakeholder perspectives on information management. Paper C reports on improvement factors for improved efficiency in information management. Paper D addresses implementation of information systems based on user sensitiveness. Paper E is reflecting the latest direction in research approach with a shifting focus from measurement to evaluation.

The way the appended papers are summarized is intended to reflect the relevancy each paper has on the thesis. To clarify this further, each summary is followed by a passage stating the overall thesis contribution for that paper.

4.1 Paper A: Introducing structured information handling in EE\(^7\) development

The paper reported on the process and outcome of a small scale IS implementation project with the purpose to support model-based development in electrical and software development. One company goal with the project was information management improvement through structured information to facilitate problems with non traceable and inconsistent information. Another articulated project goal was to provide management and designers with a good perception of how the organization’s information model for electrical and software development ought to be designed.

Among the identified success factors that lead to a positive outcome of the project were: keeping a close interaction with key users while developing the tool; and adapting the system to align with the terminology used by the designers. The fact that the tool was developed gradually in collaboration with the designers resulted in them expressing a will to assist in the change process. As a result, a tool that supported current work procedures was developed and a quick IS adoption

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7 Electrical and electronic (EE)
was achieved. By taking a bottom-up approach, a successful local implementation of the information system can be achieved and several managerial challenges overcome.

The underlying prerequisites for advantages with model-based development are:

- explicitly allowing time for organization development with respect to adopting new work procedures and IT/IS
- enhanced communication between designers with similar needs
- ontology efforts
- information modeling
- process development
- allow integration to existing processes and parallel use of legacy IT/IS

The implementation process forced the company to go through the structure of requirements and terminology used before being able to correctly state the requirements on the IS. By considering product, process and organization, a successful foundation was laid for a well-anchored use of a new support system for information management within electrical and software development.

4.1.1 Contribution to thesis

Important insights for information modeling are contributed. It is concluded that the issues to be faced when addressing model-based development are as much organizational as they are technical. The need to consider user needs in order to successfully accomplish firm establishment of the change among designers is clearly illustrated. Valuable insights are given into the balance that has to be obtained between designer and system perspectives. A combination of bottom-up and top-down approach to IS implementations must be applied to prevent full-scale integration problems caused by process changes and adaptations to system level information models. Without management support it is hard to achieve a balance between technical and organizational prerequisites for information management. A clear statement of long-term benefits with bottom-up initiatives is needed. It is also important that the introduction is based on the designer’s own will and motivation, suggesting that establishment of user needs and early user involvement in the change project are designer aspects that need to be considered. The main contribution with gradual IS development is the enhanced motivation among designers to make a change. The main drawback is the difficulties that arise when trying to align the customized IS throughout the organization, incorporating separate islands of users into the new integrated system. The results from this study led to the subsequent research Studies 3 and 4 focused on needs from designer and management perspectives to identify strategies for information management.
4.2 Paper B: Balancing operational and strategic impacts of information management

The purpose is to identify present similarities and differences with aspect to information management to achieve improved interdisciplinary integration - integration within R&D, and inter-lifecycle integration, i.e. information handover in the systems lifecycle. This is obtained by exploring the similarities and differences in experienced needs, benefits and goals within information management from three different organizational perspectives: designer, top management and middle management.

Gaps were identified between managers and designers concerning needs, benefits and goals with information management. There is an understanding among middle management that the problems perceived by designers are explained by poor information management. This corresponds well with the understanding among designers, thus the gap between the two organizational levels is relatively small. However, a misalignment can be detected between top and middle management concerning information management as a solution to problems. Short-term savings and quick fixes are rewarded by the company’s bonus system, in favor of rewarding long-term improvements, such as strategic structuring of information.

This paper also identifies another discrepancy between top management and designers’ attitudes to information management. That is to say that designers are not primarily interested in integration issues, while top management on the other hand focuses on integration and system issues, valuing the need for interdisciplinary and inter-lifecycle integration in information management. Middle management tries to streamline the SE processes, acting as a bridge between designers and top management with a purpose of better product quality and lower costs.

Differences in approach to information management exist on each organizational level and to a certain extent this should be allowed. However, as a result of having performed a closer comparison it is suggested that many of the identified needs are common throughout the organization. Several synergies can be obtained if the underlying needs are broken down and balanced so that a mutual understanding of how different terms are used in the organization can be obtained. It is suggested that if focus is made to fulfill the operational purposes, strategic purposes will also be achieved.

4.2.1 Contribution to thesis

Additional perspectives on information management were gained and contributed to the overall research understanding. The main contribution to the overall research analysis is to illustrate the importance of acknowledging different perceptions of information management and balance these differences to achieve improved possibilities for integrated information management.
Gaps exist between management and designers when it comes to the value of domain-specific IT tools and lower costs, while efficient information retrieval, structured information and higher quality are variables that both management and designers find as approved arguments for information management investments.

Findings reported in Paper B indicate that information management needs perceived at a top management level relate to process and tool integration. Designer needs are more related to information structure and efficiency in information retrieval in order to obtain reliable and updated information. Thus, while management has an articulated focus on integration needs, designers do not express integration as such to be an explicit need. However, they stress the need for improved information exchange across disciplines, coupling this to their own work efficiency rather than to improved interdisciplinary integration. This suggests that, at first glance, differences in needs seem to exist due to use of different terms, but similarities are exposed when studying the content of the terms.

4.3 Paper C: Measurement for information management performance: a model to identify improvement areas

The purpose of this paper has been two-fold. First, the intention was to verify if the proposed approach to measure information management performance could be statistically verified using the developed preliminary conceptual model. For this purpose a Partial Least Square (PLS) analysis was made to test the model’s significance. It has proved feasible to get statistically significant results by using the proposed model and questionnaire. Based on this conception, one important finding presented in the paper is the outcome of a refined research model to measure performance of information management. The second purpose was to investigate the possibilities to identify improvement areas in information management. This purpose is more context-specific and related to the identification of improvement areas at the studied company, including the possibility to distinguish specific critical improvement areas. In this study information structure, introduction and training, and user satisfaction are suggested as critical areas where improvement is extra beneficial for the company to undertake.

Satisfaction with IS and information management was used as dependent factor in the preliminary conceptual theoretical model. Based on the statistical analysis this model was refined to also include interdisciplinary integration as dependent factor. The outcome of the analysis resulted in the following main findings: information structure and information usage are two factors with high dependency to interdisciplinary integration, indicating that improvement of these factors will affect interdisciplinary integration positively; in turn, interdisciplinary integration has proved to have a direct impact on information and product quality and efficiency with aspect to information management, a result that was not anticipated in the preliminary
model; finally, no direct relation to dependence factors other than to the innovation factor could be established for user satisfaction.

It is proposed in the paper that a survey targeting user satisfaction makes it possible: to identify improvement areas in information management; to provide statistical evidence that promote efficiency to support the need for improvement measures; to provide management with a relevant set of key metrics that can be measured yearly in order to achieve continuous efforts for improvement; and to enable a method for benchmarking of other organizational company units or even other companies.

4.3.1 Contribution to thesis

The findings presented in this paper give support for, as well as complementary addition to earlier qualitatively based findings from Phase I. The paper indicates the significance interdisciplinary integration has to performance in information management, also suggesting the importance that should be given in companies to integration aspects to achieve successful information management.

4.4 Paper D: Motivation mapping method as a means to improve engineering information management

The findings presented in this paper are based on a cluster analysis with the purpose to identify groups of users with similar approach to implementations of a new information system. The paper reports on the possibility to do a separation of different user groups based on their user satisfaction, experienced benefits and perceived expectations. Characteristics on each of the identified groups are reported on in the paper. The group that qualified as the most dissatisfied user group had outcomes with both high expectations and low benefits with current support tools, suggesting that this group has a real desire to change its IS environment. The “content user group” includes people who are relatively satisfied with current IS solutions and see no obvious reason for change since they experience quite high benefits from the IS offered. The selection of groups is proposed to be made prior to IS implementations and can assist management in identifying groups of users that are more or less receptive to change. The results are intended to support management decisions on roll-out strategies. A step-wise method for mapping motivation level among users is presented. The method is based on user needs and should be used to address differences among users to enable IS implementation that is well-adapted to company-specific needs and constraints. Thus, the method enables support in tailoring IS implementations with the aim to obtain a more cost- and time-efficient introduction process. The method should be used in combination with other assessment methods for IS implementations.

4.4.1 Contribution to thesis
Findings in this paper enhance the researcher’s understanding on the importance to consider the perceived level of user satisfaction while adapting changes in organizations. Findings indicate that the more disappointed users feel with information related issues in their work, the more receptive they are to changes made in information management.

One practical implication with this approach is that level of user satisfaction, experienced benefits, and perceived expectations can be used to identify clusters of designers with varied motivation for IS support, hence identifying problem groups that need special management attention to offer adapted preparation strategies. It is argued that IS introduction strategies should be based on specific needs, such as user satisfaction level to improve user motivation. This approach is believed to lead to a more efficient IS roll-out and a higher degree of user adoption to the new technology.

4.5 Paper E: Performance evaluation of complex product development

The main purpose with this paper is to present and discuss a performance evaluation framework. The framework provides a platform for discussions on measurements and is intended as a company or management tool for communicating an integrated view on performance in product development. As such, it is presented as a conceptual framework that supports reasoning about performance both at the overall development process level and at the individual activity level. It could e.g. be used as evaluation support for the individual (e.g. a designer) conducting a particular activity, in order to relate how this particular activity contributes to the overall performance of the product development process.

The performance framework is proposed as a way to use a model-based approach to evaluate activities and aims at introducing a different way of thinking about evaluation in product development. One suggested benefit with the proposed framework is that it provides a system perspective that promotes an efficient “flow of activities”, and prevents focus on individual product development phases and specific activities. One important aspect to obtain this is the explicit integration within the framework of the goal or objective with the product development activities. The evaluation is based on actual performed activities, which provides support to define measurements that are in accordance with company specific needs. It is argued that a system perspective and the possibility to tailor criteria and measures according to contextual circumstances are needed for performance evaluation to improve work in product development.

4.5.1 Contribution to thesis

As argued in the paper, the need for accurate information is crucial to make use of the activity model. All product development activities rely on information input such as end user requirements, technical specifications or test and verification values, and much of the efficiency
carried out in these activities are dependent on information structure and availability hence there is a strong interrelationship between product development activities and information content. Performance activities in general are approached in the paper, but the framework can take a specific information approach and be used to evaluate information management specific activities, and thus makes an important contribution to the discussion on use of measurements. It is argued in the paper that a discussion about what the information consist of – based on defining what the input and output is, and what information needs to be transformed – supports an increased understanding in the organization of what it is relevant to measure, and aids the design of metrics. The way information is presented becomes more well-defined by questioning the state of information and “giving” it precise meaning and relevant content.

The paper includes a discussion on possible benefits of the proposed framework in design projects, although these have not yet been fully evaluated or proven. The paper is appended since it contributes with expounded reasoning to some of the reflections used in the discussion and gives input for further proposed work.
5 DISCUSSION

The discussion presented in this section is based on a synthesis of the overall research findings and aims at revisiting the research questions (RQ1-RQ3) in an attempt to answer them.

5.1 What key factors are important for efficient information management in complex product development?

Based on the initial findings from research Phase I, five key areas were stated as important for efficient information management (Malvius 2007): motivation; information structure; organizational support; information usage\(^8\); and interdisciplinary integration\(^9\). In Phase II these results were further refined to include the ranking of identified factors (Paper C). Based on a combined synthesis of research findings from Phase I and II, two factors were identified as being particularly important for efficient information management: interdisciplinary integration and information structure.

5.1.1 Interdisciplinary integration and structured information

Interdisciplinary integration and structured information are both related to integration. Interdisciplinary integration relates to the collaboration and interaction of humans involved in design engineering, whereas information structure relates to integration of information and addresses the way information is organized and presented. Having structured information implies having a core notion of the information that is required to describe a system. Structured information is suggested to help provide and maintain consistent and complete information, and maintain traceability within and across views (Larses 2005). In the case of interdisciplinary integration the expected result is quite straightforward suggesting that collaboration between designers from different engineering disciplines will have a positive effect on efficiency with regard to information management. Similar conclusions have been made by Kahn (1996) on an interdepartmental level and with respect to performance. When it comes to information structure, the relationship to integration is more implicit in nature and in need of a more thorough presentation and discussion here. Stevens et al (1998) state that requirements need to be

\(^8\) Referred in Malvius (2007) as usability
\(^9\) Referred in Malvius (2007) as integration of information
structured to detect missing requirements, overlaps and allow them to be viewed at different levels of abstraction. It is argued that the same must apply not only for technical requirements, but for all product related information used in product development. It is also argued that the information needed to achieve efficient product development can already be found in existing IT/IS in organizations, but that it cannot be efficiently exchanged due to a lack of structure and mutual understanding of the content of the information. If information is poorly structured, then it may be overlooked even though it is available, or engineering designers may be unable to locate it in the available time (Macleod et al. 1994). Problems related to information management - like incorrect and not updated information, or insufficient version and configuration management - cannot be solved by implementing a new information system. Instead, management should shift their focus within IT from the T (technology) to the I (information), and seek to provide the means to accomplish a unanimous definition of concepts and structured information (Carlsson et al. 2007). Hallin et al. (2004) also stress the importance of having an information focus instead of an information system focus in order to obtain integration of information. Although indirect in character, information structure is proposed as one main underlying factor for success with efficiency goal efforts in information management. The importance of considering information structure in product development is supported by Yassine et al. (1999) who promote an information structure perspective to manage the interactions manifested by the information exchanges within the design process.

It is important to stress the close relationship and interdependence between interdisciplinary integration and information structure. Reflecting on the relationship between these two factors, it is argued that information needs to be structured to be able to align (“tie information together”) for interdisciplinary use. Information structure can be perceived as one underlying means to support interdisciplinary teamwork, as confirmed by the resulting model presented in Paper C. Interdisciplinary integration and information structure are considered to relate to several aspects of information management in product development, and are frequently recurring in the overall discussion.

5.1.2 Co-existing goals and information usage
In the following sections, the allowance of co-existing goals and support for information usage are discussed since they are proposed to have an influence on efficiency in information management.

Contrary to the management case discussed in Paper B, designers expressed goals explicitly connected to efficiency improvements in information management. Furthermore, the goals were precise and included suggestions of concrete improvement areas. Management goals on the other hand related to cost and quality gains in general and were more vaguely formulated. This is in line with Davenport (1993) who states that there is little focus by senior management on the information itself. One suggested approach to manage differences in goals concerning the efficiency of individual work tasks and cost/quality goals is presented in Paper B. It is suggested
that different goals can be managed – with a probable effect of aligning them in the end – if conflicting goals are managed through the identification of underlying needs among designers and managers. A needs-based approach is discussed in more detail in Chapter Balancing needs. Adler et al. (2003) argue that conflicting goals must be resolved to achieve progress, and therefore the goals among team member groups as well as areas of agreement must be known to designers so that they can identify where such goals are in alignment and where potential conflicts may arise. Communication of reasons for existing differences is expected to lead to synergies based on the understanding that differences in goals to a large extent can be explained by different level of goal focus: operative vs. strategic – and that attending to operative goals and meeting designer needs, in the end possibly will lead to fulfillment of strategic goals. In cases where a misalignment between individual and formally stated goals can’t be overcome, it is suggested that communication still could provide enhanced understanding of differences and make the need clear for e.g. disciplinary adjustment in order for a team to be able to meet the stated goal or for adaptation of strategic goals to fit (more practicable) operational goals. The need to improve internal communication among team members as a means to better define goals and improve performance is also addressed by Ancona and Caldwell (1992).

Although strategic goals are also needed, it is important that management succeeds in stating accurate goals with information management, and that they address areas that are relevant to efficiency. It is suggested that co-existing goals will make a win-win situation possible to designers and management since it is proposed that the fulfillment of operational goals will lead to enhancement of strategic goals. Where different types of goals should co-exist, this is regarded as the most favorable solution. Where an alignment of goals needs to be reached, it is proposed that a shift from strategic goals to operational goals is necessary. After all, efficient information management is dependent on the possibility to support designers in their everyday work, and when it comes to information management this goal should be the priority for organizations.

Interdisciplinary support is highly dependent on information usage. (In the statistical analysis in Paper C this relation is made very clear, however this statement is also based on qualitative findings, thus based on a synthesis made to the overall findings). This implies that the way information is used (e.g. create, search, share, store) has an impact on collaboration and interaction between engineering disciplines in an organization. Model-based work has proved to be one important variable included in the scope of information usage. The importance of working with models (UML, flowcharts, state charts etc.) in comparison with document-oriented information processing (textual requirements specifications, Powerpoint™ etc.) is further elaborated in Chapter Model-based development.

It is reasonable to argue that interdisciplinary integration is either strengthened or weakened depending on a designer’s need for information. The overall reasoning might be that for example, a software designer with a great need of reading design models produced in CAD tools in order to accomplish their own work is likely to actively access information from the mechanical engineers concerned, thus positively affecting the level of interdisciplinary integration. If on the
other hand the need to push information is greater, the designer is less likely to approach other disciplines for information. Detailed ways to process information hasn’t been studied explicitly in this research. However, related research on individual activities such as for example information use (Lowe 2002), information searching or seeking (Wilson 1999; Hertzum and Pejtersen 2000) and information retrieval (Wallace 2006) demonstrates the lack of interdisciplinary method support for information usage. A combined overall research understanding of the importance of information processing activities suggest that ways to enable adapted information usage could be one possible approach to enhance interdisciplinary integration.

The first research question has explored prerequisites for efficient information management. The aim has been to support engineering information activities in complex product development, and to provide management with key areas for efficiency. These areas can be broken down further to include only factors that are proposed as critical to achieve improvements in information management.

5.1.3 Critical improvement areas

*What factors are critical to achieve improvements in information management?* Once again, areas that relate to information structure have been perceived by designers as critical. To such an extent even that they are crucial to come to terms with in order for them to be able to do their job properly. In Paper A the lack of structured information is identified among designers as the main inefficiency problem. The benefits of improved information structure is also reported in Paper C, only this time the finding is based on quantitative analysis. Bergsjö et al. (2007) discuss the importance of coming to terms with factors related to information structure, such as version and configuration management. Hence it is argued that efforts to improve information structure should be an important part of management strategy.

Satisfaction with information management and IS among designers is a factor that has been identified as important to address connected to improvement work in information management (Paper C, Paper D, (Bergsjö and Malvius 2006)). This is not the same as to say that it is a critical factor to improve, rather it is important to identify levels of satisfaction among designers to be able to fit organization-spanning changes to different groups of designers based on user satisfaction level so that the change work becomes beneficial to the overall organization. Many of the respondents in the case studies were designers, and there was a strong tendency to rank satisfaction highly in order of importance, implying that designers themselves feel that this is an important factor to address. The relevance of attending to user satisfaction in the context of IS implementations has been addressed in previous research (Zviran et al. 2005; Wu and Wang 2006).

It is suggested that the resulting research model (presented in Paper C) can be used in organizations to identify key improvement areas as well as critical areas in relation to
information management. The model reflects which factors the respondents are not satisfied with, as well as the level of significance for individual factors. The combination of high impact factor and low index value helps to identify areas with high improvement benefits. In comparison, the survey results help to eliminate areas within the scope of the model where designers experience a high level of satisfaction, implying that these areas don’t need to be prioritized in a future improvement project. However, having said this, it is important to point out that one important result with this research is to underline that the intention should not be to provide any general answers to research question 2. Instead, it is argued that the outcome of specific critical areas is context dependent and needs to be addressed and refined for each individual organization, and also that the relevancy of recommended metrics should first be verified through company contextual evaluation based on e.g. activity modeling (Paper E).

One implication with identifying critical improvement areas is that they can be used as an incentive for management to approve investment in information management. However, it is proposed that, although the possibility to identify critical improvement areas is one step towards addressing change work, these results are not enough to identify concrete improvement efforts to be carried out; further discussion about the implications of implementing the identified factors is needed before an organization takes practical measures, leading to the answering of RQ2.

5.2 How can organizations enhance and take the identified factors into account?

As an attempt to answer the second research question, concrete actions that organizations can implement to achieve improved information management in product development are considered. The basis for this discussion is the understanding that interdisciplinary integration is a major dependent factor to achieve efficient information management (as stated in answers to RQ1). Model-based development and balancing needs to enable realistic expectations, as well as evaluation as a basis for measurement, are proposed as a means to align with interdisciplinary integration needs.

5.2.1 Model-based development

MBD is proposed as an important approach to support interdisciplinary integration and efficiency with information management. In this research, MBD has been approached from an organizational perspective, but the importance of MBD as a means to manage multidisciplinary complexity has previously been stated in research focusing on technical issues with MBD (e.g. Larses 2005; El-khoury 2006). Based on findings from another study with an organizational focus that aimed at exploring the possibility to use MBD to improve interdisciplinary integration, Adamsson (2004) concludes that gaps between disciplines were found although MBD was adopted strategies at the studied companies. One suggested explanation for this could be that the
modeling approaches within the organizations only were locally used, i.e. not connected between disciplines in a structured manner. Malvius (2007) suggests that a distinction should be made between Intra MBD (disciplinary) which focuses on process support, models and tools that typically are in use by one specialist discipline, and Inter MBD (multidisciplinary) which strives for integration of models and information and to include multi-disciplines and cross-functional organizational units.

It is argued that a textual-based work approach has, directly or indirectly, contributed to many of the inefficiency problems that can be identified in information management (Paper A). This perception is suggested to be compared with Kahn (1996), who states that the exchanging of information documents is one obstacle to product development performance. Information is often spread over several documents and insufficiently structured, which forces a need to focus on the documents themselves when looking for the correct information (Paper A). It is argued that a positive outcome of MBD is dependent on a combination of textual and model-based information. This is supported by Stevens et al. (1998) who state that both textual and graphical notations are essential to meet the demand of different people involved in the design work. Thus, the aim should not be to use models exclusively; instead models should be combined with textual requirements and information to provide clarification and nuanced descriptions, such as e.g. explaining the background or reason for why the requirement has been stated. Leveson (2000) stresses the necessitate to consider human needs with requirements specifications, stating that specifications need to integrate both formal and informal development aspects to support human problem solving. An ideal information support system for designers should be capable to provide access to formal engineering documents and to information that is enclosed in e.g. letters, reports and customer feedback (Lowe et al. 2004). It is relevant however to consider how this added (textual) information should be combined with models. Considering for example the use of notations, i.e. internal “notes” or “post-its”, it can be argued that this method of storing information makes it difficult (if not impossible) to retrieve and integrate information via different IT tools, since it often is inherently stored in the expert tool, with limited possibilities for external information retrieval or search options. It is proposed that textual refinement to MBD in this way can increase problems with e.g. information retrieval if structure is not considered a main issue. Hence, it is suggested that structure should be considered when adding informal information connected to MBD.

Joint ventures initiated by manufacturers, suppliers and tool developers within the automotive industry promote MBD as one solution to come to terms with related information problems (see e.g. ongoing project initiatives AUTOSAR\textsuperscript{10} and CESAR\textsuperscript{11}). Nevertheless, both organizational and technical obstacles need to be overcome before MBD can be successfully implemented in development. The transition into MBD is a gradual change work that poses several challenges to organizations; in addition to the combining of different views and problems with unstructured

\textsuperscript{10} www.autosar.org
\textsuperscript{11} https://cesarproject.eu/index.php
information, it is argued that a shift in mind-set from document-oriented to model-oriented development is needed among designers. Knodel et al. (2005) suggest that the migration to MBD can bypass common technological change problems from the beginning and minimize typical introduction problems like technology skepticism. This is probably true, but considering the required change of mind-set, it is argued that the proposed automatic transformation by Knodel et al. is less likely to gain effect.

It is recommended that companies need to consider if they aim to implement Intra or Inter MBD (this strategic decision should preferably be made prior to implementation). By reflecting on what organizational unit(s) MBD should be implemented in, necessary strategies and goal adaptations for the intended unit(s) could be formulated. This way, there is time for the change process to adapt to a new mind-set and adjust to new processes and work requirements. For reasons stated above, the transition into MBD is a process that takes several years to accomplish. Meanwhile, designers experience acute problems that need to be solved today. Therefore, it is proposed that Intra MBD should be prioritized in organizations to solve some of the immediate problems for engineering disciplines and allow a gradual shift from the existing document-oriented development. When the technical prerequisites (such as tool support) and organizational prerequisites (such as adapted work procedures) have matured, measures for Inter MBD should be taken in organizations to enable enhanced interdisciplinary support, which also includes the learning among designers to interpret model-based information from other disciplines. Paper A lists some of the organizational requirements that need to be addressed in order to work in a more model-based way, including: the application of MBD requires adaptation to existing processes; a disciplined approach is required involving both management and designers; and agreement is needed on the need for a defined information model.

**Information models**

A close relationship between MBD and information models is suggested. One basic idea is that the structure of information needs to be designed in a formal and conscious way through information models or information flows that state relationships between information objects in an explicit way. Information models are essential to enable systems integration in that they describe how information objects used in systems development are related to one another (Sellgren et al. 2009), hence offering a possibility to structure and formalize storing of information. Sellgren et al. further suggest that the definition of an information model that captures fundamental dependencies is considered a basis for synchronization of different involved engineering disciplines, since definition of dependencies is suggested to ease understanding across disciplines. Although basic, in reality this structure is difficult to obtain in a complex product development organization, as observed in the studied companies. For example, the company in Paper A had to address the issue of establishing an information model robust enough to cope with continuous adjustments. To allow for this type of built-in flexibility, information models have to be based on open source standardized interfaces such as STEP and UML/SysML (Sellgren et al. 2009). In addition to the challenges arising from the frequency of
adjustment, the attempt to design partial information models also proved unproductive since problems with incompatibility made it difficult to integrate these into a complete information model (Paper A). One explanation for the lack of overarching information models might be that the complexity of realizing a system-spanning information model is just too great, with the probable outcome likely to be too difficult to use and manage – thus defeating the object. This relates to a key issue in modeling, namely that of understanding the goals of the models and as a result finding suitable levels of abstraction (entities, properties, interrelationships) that are useful given the stated goal.

5.2.2 Terminology

The search for information is complicated due to the use of multiple words for the same phenomena or the same word used to mean different things. MBD is suggested to be an important tool to align the understanding of different concepts used in design, since it promotes a discussion around the information embedded in the models (Paper A). This is supported by Axelsson (2002) who suggests that modeling in itself promotes a consistent language and use of terminology. This is also in line with findings by Zimmerman et al. (2006) stating that the use of models is an important instrument for the creation and integration of concepts.

The topics of MBD and terminology are also suggested to be interrelated in another way: in some sense, the existence of a partially mutual understanding of basic concepts could be seen as a basis for MBD. This is supported by Adamsson (2004) who proposes that aligned terminology is one important prerequisite for MBD. The importance of a coherent design language for integration of information is acknowledged in literature (Mortensen 1997; Doerr et al. 2003). Doerr et al. argue that core ontology is one key building block to integrate information from diverse sources. Borst et al. (1997) discuss the practical use of ontology for engineering systems modeling, simulation and design, and suggest ontological super theories consisting of generic building blocks to enhance knowledge sharing across engineering disciplines. However, it is argued that in a complex product development environment, company-wide consensus around the use of terminology or the accomplishment of a common ontology is a utopia that is more or less impossible to achieve between people with different understanding and backgrounds. One reason is that designers are not willing to adapt their terminology to external definitions, sometimes even indicating language barriers within one discipline (Paper A). Consequently, it is proposed that ontology should not be the goal, especially since some degree of ambiguity needs to be allowed in product development. Instead, a mutual understanding of terminology should be considered a reasonable and feasible goal. It could be argued that MBD to some extent enables this goal as well by supporting differentiated use of terminology. This notion is contrary to Adamsson’s (2004) who states that common values and attitudes could not be achieved by MBD, but are a necessary pre-condition for MBD. However, considering that there is an outspoken company strategy to work model-based, one suggested effect would be to communicate disciplinary models between disciplines, which in turn would enhance the understanding of different use of terminology. Made proposal is also based on the understanding that MBD
incorporates formality, stability and sharing scope, which are three dimensions of information proposed to have fundamental impact on the usefulness of ontology for information management (Elst and Abecker 2002). In all circumstances, above reasoning implies that there are interchangeable benefits between MBD and terminology.

5.2.3 Balancing needs

Different perspectives of needs, benefits and goals with information management have been studied and compared throughout this research: IS user perspective (Bergsjö and Malvius 2006); management and designer perspectives (Paper B); electrical, software and mechanical perspectives (Malvius et al. 2007b); and consultant, vendor and user perspectives (Malvius et al. 2008). It is argued in the following that balancing different or diverging information needs is one of the main tasks management must face in order to come to terms with inefficiency in product development. Two approaches are proposed in this research to identify and manage differentiated and conflicting needs: a strategic selection of supporting terms that are beneficial in achieving organizational goals at the same time as they act as motivation for the designers (Paper B); and a “shifting lead” approach to manage needs-based trade-offs among IS users (Malvius et al. 2007b). The intention with the shifting lead approach is to allow IS user groups or departments with a dominating need to take the lead in customization and pre-study IS implementation projects. Balancing disciplinary needs this way suggests a means to adapt IS functionality and increase IS use efficiency.

It is suggested that the process as such, of balancing needs in an organization supports a common understanding of what the overall needs are in product development. It is argued that multiple viewpoints and involvement of multiple disciplines should be regarded when considering a balance between different needs. One possible effect of this might be a transfer towards needs that endorse interdisciplinary integration. After all, existing needs may be modified by the new information gathered in the process – in which case, according to Argyris and Schön (1978), the organization has already learned something of value. An increased understanding of how existing needs among designers and management affect each other might support consideration of system interdependencies. Organizations need to attain a wide understanding between designers and involved stakeholders of the system that is being developed, since information needs to be readable to multiple stakeholders along the life cycle. This brings them together as an integrated team, reflecting the need to produce accessible information.

Designer needs are also taken into account in information push (Campbell et al. 2004; Campbell et al. 2005) and pull strategies. In both cases access to structured information stating relationships between information objects is suggested as one prerequisite since existing strategies rely either on the possibility to anticipate and pre-define needs (push) or on the designer’s own knowledge of what information he/she wants to request (pull). This suggestion is based on the understanding that needs in product development are dynamic and a suggested
framework should support changing needs. This is especially true since information searching in itself includes activities for identifying a person’s own needs for information (Wilson 1999).

**Intrinsic motivation**

Thus, the stand-point taken is that information needs among designers should act as the driver for efficiency improvements in information management. One underlying reason for this proposal is based on the understanding that motivation is intrinsic (Nicholson 2003) and therefore information needs have to be initiated and realized by the designers themselves. The identification of motivation level is important since the question of how to approach people with low motivation levels has practical managerial implications. According to Nicholson (2003) an entirely different managerial mind-set is needed for employees with low levels of motivation, since management can’t motivate these “problem people” - only they themselves can. The proposal of a needs-based approach for information management is in line with Nicholson’s statement that a managerial shift in perspective is needed to help remove barriers: instead of pushing solutions on employees, the manager should pull solutions out of them by creating circumstances in which the employees can channel their motivation toward achievable goals.

The influence that existing structures in organizations and society have on overall information needs must be acknowledged. These can be social, environmental, cultural or other aspects that have a definite affect on the information content and need. At a generic level the evolution of design information is dependent upon several factors: whether it is a routine or a non-routine design problem; the organizational structure and culture; the type and the size of industry; the complexity of the products generated; the level of expertise and technology involved (Majumder et al. 1995). It follows that these structures need to be considered, in addition to intrinsic motivation, as having an influence on the perceived need among designers for certain information.

**Information mapping**

Mapping the need for certain information content is proposed as one approach to identify similarities and differences with needs among designers. The framework presented in Paper E, based on the IDEF0 framework (Colquhoun et al. 1993) is proposed as one means to achieve information mapping. Similar approaches to information mapping have been proposed previously in research (e.g. Rangan and Fulton 1991; Court et al. 1996) as one method to understand the design process and to define data flow models that reflect the process. In practice, one way to accomplish information mapping through the use of suggested framework might be to equate the information required in management plans to information deliverables that are needed in the development project. Management plans are used in this case as input for the intended goal. The framework implies evaluation of a performed activity compared to its overall benefit to stated goals. When analyzing how an individual’s work input relates to the stated goal, designers and managers need to understand and reflect the value of performed activities and in what way they contribute to fulfilling the stated goal for that activity. It is suggested that
mapping information against goals set by management provides an outline of when and where in the product development process specific information needs to be provided. Berryman (2006) states that one reason for uncertainty in information seeking and retrieving is that the tasks are often vague and unstructured, resulting in difficulties understanding what the scope of the work is. It is argued that the proposed framework obtain efficiency effects since it helps to identify what activities that are necessary to perform to be able to fulfill the stated goal, and that this also implies elucidating unnecessary or redundant activities. The framework is suggested fit to address conflicting needs that exist due to different perception of intended information demand. This is argued for two reasons: the demand for information lies as the foundation for information flow or transfer when using the framework; and the need to integrate information produced in different organizational functions and on different system levels is highlighted from the outset. Sosa et al. (2007) suggest a similar approach to obtain information about communication patterns among designers. This technique combines the results from interviewing systems architects and surveying component designers into a matrix that reveals mismatches between the communications and exchanges that are supposed to occur and those that actually do. It is argued that these methods should be used in a complementary way, suggesting that the proposed framework (since it relates to the stated objective with the activity) could contribute to increased understanding of systems (including e.g. resource or stakeholder interests in addition to product) inter-dependencies through enhanced communication of the overall need of information in specific phases, while the alignment matrix is suggested as a next step to provide enhanced communication by focusing on unattended and unidentified interface issues that specifically relate to the physical product.

Identification of what information needs to be exchanged when is suggested to contribute to improved interdisciplinary integration. The process of distinguishing and sorting out significant information that needs to be produced requires different competencies and engineering disciplines to communicate their needs with regard to information sharing and exchange. This is proposed to have the effect of increased awareness among designers not only of design issues, but also of the other involved parties that will need to share their information. It is critical when planning a complex product development process that the project managers specify just which resources and information different teams will need from each other at particular stages of the project (Sosa et al. 2007).

5.2.4 Evaluation as basis for measurement

Measurement of user satisfaction (Paper C) is one attempt to provide a way to perform initial measurement on a general level to identify areas of improvement for information management in complex product development. However, the task of implementing a measurement system is difficult and iterative due to constant changes in the business environment, implying a need to adapt and update the research model used as basis for measurement so that it fits specific needs suited for that particular organization. A mapping of existing metrics for information management, and in particular IS implementations (Malvius et al. 2008) concludes that
measurements need to be tailored and take into consideration particular contextual prerequisites to fit dynamic organizations. As concluded in Paper E, success indicators need to be designed and maintained; otherwise the different metrics will not remain relevant and useful for organizations. This is supported by Neely et al. (1997) who state that the key issue in designing measures of performance is that they have to be matched to the organizational context.

It is further argued that metrics need to be kept in line with the business and development strategy (Paper E). The need to align with existing strategies is also pointed out by (Loch and Tapper 2002) who propose a strategy-driven performance measurement system. It is argued that if consideration of strategies is not made when designing metrics, measurements are just as likely to hinder successful improvements in organizations. This argument is based on the understanding that metrics play an important role in organizations since their application is widespread and the measurement outcome acts as the basis for strategy decisions, hence influencing changes in strategy. Inadequately designed performance measures can result in dysfunctional behavior, encouraging individuals to pursue inappropriate courses of action (Neely et al. 1997). One explanation for this might be that the development of quantitative performance measurements grew out of the notion that if progress toward goals can be measured, efforts and resources can be more rationally managed (Ridgway 1956). Making this assumption, the need for tailored metrics is evident since it is easy to realize what the consequences of using misleading metrics would be for an organization’s strategy.

Insufficient communication and the use of old and irrelevant information in design work are some of the reasons that makes it necessary to cope with changes in complex product development (Fricke et al. 2000). In addition, overall changes are necessary to stay competitive in today’s dynamic business environment, which makes it important that means for metrics update can be offered in an iterative manner to keep up with a changing environment. Thus it is argued that the use of metrics needs to be done in a dynamic way. It is argued that companies themselves are fit to do this adaptation work since they have the inside perspective. The framework presented in Paper E is an attempt to provide companies with a complementary evaluation support for internal identification of important performance criteria. By focusing on which factors are important to measure, the proposed framework can be used to design new measures or identify relevance among existing measures. Once these factors are established the research model proposed in Paper C can be refined based upon the company’s specific needs.

5.3 What expected benefits does integrated information management entail?

The final research question is hard to answer since integrated information management is not fully practiced in reality, which makes research on the subject difficult to study. Overall anticipated efficiency gains with integrated information management are released capacities in
organizations in terms of, for example, more time and resource-efficient design work, as well as creativity gains. It is also suggested that efforts to achieve integrated information management will lead to benefits with increased information availability, reduced information overload, and enhanced communication and understanding.

5.3.1 Increased information availability

Enhanced information availability in organizations is suggested to be one probable efficiency benefit with integrated information management. For example, information availability is to some extent enabled by the existence of a formalized information structure. Ideally, integrated IS is also considered to be of support to increased information availability since it facilitates the acquisition of information.

Why should increased information availability be considered such a benefit? Increased information availability does supposedly have an effect on decision-making, for example, in the sense that it prevents sub-optimized decisions as the information used as a basis for decisions is made more accessible and possible to overview. Modeling has proved to be an interactive support for decision-making in other domains (Wierzbicki 2007). Information that can be accessed immediately facilitates management functionality such as interdisciplinary engineering change management and configuration management, as well as data integrity (Bergsjö et al. 2007). However, information that is available but difficult to locate makes information inaccessible, which leads to a tendency to base certain decisions on incomplete information and assumptions (Rangan and Fulton 1991). Availability probably also has an influence on what product development activities are being performed, since a change in information availability may result in a call for certain tasks while others become redundant in light of the new information. It is suggested that with the potential to acquire and get constant access to updated information, a better work continuity is made possible, reducing the risk of occasional work overload (Paper A). However, an increase in information availability requires other process-based means of control to ensure that more or less unhindered information access is not becoming a severe problem in itself due to e.g. information maturity and quality issues. This risk is addressed by Loch and Terwiesch (2005) who present a model to manage decision-making based on preliminary information.
5.3.2 Reduced information overload

If managers become more explicit in formulating their information needs to designers, and formulate to what purpose they require the information; and If designers spend more time reflecting upon what the information needs look like from a system perspective, rather than having to spend time on twisting and producing information to achieve the requirement for information to fit designated forms… Then it is argued that the information content relevance would increase, and that organizations would eventually come to terms with the information overload. In an ideal world, the amount of information could instead strive towards optimization, resulting in reuse of information instead of information padding, “tipping the pyramid over” (Figure 12). In practice, it is argued that this change implies the need for a shift in mind-set where designers focus on communicating information, valuing information, questioning information, and so forth - in short: there is a need for organizations to approach information from a needs-based stand-point and to take on an information perspective to all activities in product development.

5.3.3 Enhanced communication and understanding

Adopting MBD in organizations is proposed to be important for improved efficiency since it is suggested to enable foundation for more structured and “context-based” information. Thus, one expected contribution with MBD is structured information (Figure 13). Information structure is one important pre-requisite to facilitate information processing by providing relationships between information objects and indicating probable placeholders where relevant information can be found. The contribution that MBD makes to more consistent and structured information is also considered one possible support for aligning information in a standardized way (Törngren et al. 2009). Information structure is proposed to give support for increased traceability between requirements, which is suggested to for example facilitate verification through enhanced review and testing.
One proposed benefit with MBD and consistent information is support for gaining a deeper system understanding and improved basis for communication (Figure 13). Hansen and Andreasen (2004) state that the “output” or result of requirement specifications has to have a form and content which makes the communication of stakeholders’ vision feasible. In addition, communication based only on text will have a very low communication value, and the certainty in interpretation is also low (Österlund 1997). In MBD, computerized models are used to support communication, documentation, analysis and synthesis, as part of the systems development (Törngren et al. 2009).

Following similar reasoning, mutual understanding of terminology can be seen as a contributor to improved communication and enhanced understanding among designers (this is suggested to be true even if no consensus on the terms is reached among designers). This line of argument is supported by Österlund and Lovén (2005), who address the same issues, namely the need for a good information structure and an existing culture of common terms and values to be able to obtain a learning process. They conclude that in order to get a learning process started, management need to provide a variety of updated information to suit the organization.

Figure 13 Information structure is one anticipated benefit with MBD and a mutual understanding of terminology. This in turn provides support for enhanced communication and improved understanding.
Knowledge, attitudes and communication abilities between different engineering disciplines is suggested to lay the foundations for successful and synergistic systems development. The use of models has for long been recognized to achieve efficiency and support design work. Models play an important role in systems development since a reduction of both complexity and information is achieved by modeling (Fricke et al. 2000). Information presented in a model, if presented correctly, is suggested to help individuals to make better decisions. Models can also be used to affect changes in decisions since they help to visualize possibilities and problems to decision-makers. Zimmerman et al. (2006) who have studied cross-functional integration state that the use of models is important as a means for communication and decision-making for people in coordinating positions, such as project leaders and systems engineers.

One of the anticipated benefits with integrated information management is enhanced visualization of information that needs to be shared between engineering disciplines. MBD supports visualization of multiple modeling views for use in analysis or design and provides designers with improved information on relationships between information objects. This is suggested to have an effect on the understanding of the need for early simulation and testing as well as understanding of pre-requisites for e.g. systems integration. The challenge however is to relate these views to each other – a task that could be seen as part of the information structuring.
This research has aimed at taking a systems thinking approach to information management in complex product development. The research focus has been on the integration (collaboration and interaction) between engineering disciplines where software and electrical R&D departments at automotive companies have been the main source of the analysis material. Based on different perspectives on information management in complex product development the following can be concluded to be overall key issues to address. A combined bottom-up and top-down perspective is concluded to be an efficient approach to come to terms with challenges in information management. This implies a consideration of information management issues from different perspectives, including a technical and an organizational perspective, as well as perspectives on several organizational levels such as e.g. operational and management level. It also encompasses the need for co-existing goals with information management. From an information efficiency aspect it is concluded that operational goals need to be attended to in order to achieve strategic goals with information management. Further, it is concluded that balancing needs is important to reach a feasible solution to changing and conflicting needs that arise from dealing with complexity in product development. Finally, when it comes to concluding the suggested move towards a “middle alignment”, a mutual understanding of terms is stated as a realistic and pragmatic strategy that shifts focus from change efforts with company-wide use of terms to enhanced communication and understanding (and possible consensus) around existing terms.

One common factor for the identified key areas for efficient information management is integration. Interdisciplinary integration and information structure both aim at integration outcomes and are concluded to be of main priority for successful information management in complex product development (Figure 14). Well structured information constitutes the solid ground that companies need in order to obtain efficient information management. In turn, MBD is concluded to be considered a significant means to obtain information structure. MBD is also concluded to be an important approach to improve interdisciplinary integration since it enables visualization as basis for communication. Visualization of relations between information objects through the explicit use of models helps to illustrate information flow and systems interdependencies, resulting in a deeper understanding among designers of how changes may affect the overall system, and making explicit the need for interdisciplinary integration. Two overall suggested benefits include improved support for decision-making and reduced information overload.
The satisfaction level among information systems users is suggested as an angle of approach to measure performance with regard to information management in complex product development. Measurement is based on a developed research model intended to identify key improvement areas from an operative perspective that are argued to be strategic for management to come to terms with. However, the need for adjustments to contextual prerequisites and a changing environment makes evaluation necessary prior to measurement. An evaluation framework is therefore proposed to identify metrics that are tailored and kept in line with business and development strategies to ensure that they are relevant and updated.

It is concluded that an information-based approach in product development is needed to come to terms with inefficiency. By adapting an information mind-set in organizations, the relevancy of and need for information is addressed and considered in relation to different design activities. Two approaches are proposed to achieve resourceful information-oriented activities: addressing differences in motivation and needs; and evaluating activities in design work. The information needs among designers have to be communicated between engineering disciplines to map information content and grasp interdependencies.

The presented improvement areas for information management in product development are suggested to be relevant and important for organizations to come to terms with. However, there still are several other factors that have an impact on efficiency in information management. This research has tried to take a systems perspective approach and focus on factors that are beneficial to improve information management. It is concluded that this research brings together urgent viewpoints that are relevant to obtain integrated information management for complex product development, but without attempting any claim to have offered a complete picture! The suggestions and conclusions drawn in this research offer a valid representation, however it is stressed that there are others. Rather than prescribing detailed solutions on how to succeed with integration with regard to information management, the work attempts to enhance understanding
and offer a more nuanced picture of obstacles and possibilities for information management in complex product development.

People involved in complex product development are perfectly able to realize system interdependencies, achieve with problem-solving and make logical decisions if they are provided with the correct infrastructure. In the context of information management in complex product development this includes support for information structure and foundation for improved collaboration. Instead of e.g. trying to gain automation with information activities in every phase of design work, or adding extra functionality to IS, it is argued that focus should be on fulfilling fundamental operative needs among designers.

6.1 Future Work

Organizational strategies are lacking when it comes to implementation of MBD in organizations since much focus is put on technical integration issues such as IT/IS platform support and integration of modeling views. It has been concluded that companies need to prepare the organization when implementing MBD, and to consider the time issue when a need for a shift in mind-set among designers is required from document-oriented to model-oriented development. For example, one suggested distinction should be made between Intra (disciplinary) and Inter (multidisciplinary) MBD, which is suggested to be one area for future research. A broader MBD scope is proposed that incorporates organizational aspects to a larger extent. The possibilities and benefits of applying MBD principles for information modeling, and activity modeling for performance evaluation on process modeling, could also be further investigated. One proposed research area is the evaluation of the benefits of MBD, looking at the short- and long-term added values for an organization. It would for example be relevant to study what effect MBD has on product development performance.

It is important to further study pre-requisites for the change process among designers when adapting MBD, since little emphasis is made on this subject in research to date. (As of today, organizations are experiencing this transformation in practice). This includes the question of what motivation aspects (learning, expectations, IS maturity etc) need to be considered to succeed in transforming from textual-based to model-based driven development. One possible outcome would be suggested strategies for MBD adaptation. If possible, such research should include longitudinal studies since the transformation is a long-time change process, and should preferably be based on action research to make direct company improvements possible.
6.2 Concluding remarks

Waring and Wainwright (2000) present a comprehensive study on integration with respect to information systems. It is argued that their study is relevant when addressing the use of integration in the context of information as well, since they take a wide scope and study the use of integration as a concept in multiple domains (technical, systems, organizational and strategic). They present a variety of definitions of integration but conclude that there is no easy or single way to define integration. This is an important finding for the understanding of the suggested concept of integrated information management. The intention behind establishing this term is to introduce a systems thinking approach to information management. It should be used as an open-minded concept with the potential to integrate (striving to include rather than align) different perspectives and dimensions in the context of information management. In this thesis, the human perspective has been somewhat emphasized. In other contexts, this might not be appropriate. No formal definition is offered arguing that there should not be any static interpretation of the concept, since new and changing demands on information management will most probably arise, implying the need to include new factors in the definition. Rather, it is suggested as a conceptualization of the need to approach information management issues with an integration perspective.


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