Mechatronics engineering
New requirements on cross-functional integration

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Mechatronics engineering – New requirements on cross-functional integration

Niklas Adamsson

Licentiate thesis

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Abstract

Several industrial sectors experience an increased reliance on mechatronic systems as electronics and software are being embedded into the traditional mechanical systems of these industries. Important challenges within mechatronics engineering come from management of multi-disciplinary development project teams and the highly complex scope of problems, which in turn require extensive coordination and integration, both in terms of technical and organisational matters.

The concept of cross-functional integration in product development research has in previous research mainly addressed integration of the functions marketing, R&D, and manufacturing, and whereas the present thesis is delimited to include only the R&D organization and the functions and engineering disciplines within such an organization.

The purpose with thesis has been to investigate mechatronics engineering in order to understand and explain how cooperation, integration, and knowledge sharing between engineering disciplines can be supported. This research has been realized by empirical studies in mechatronic development settings in engineering companies, but also by taking part in industrial and academic research projects that develop and study computer-aided mechatronics engineering.

Findings presented in this thesis show that mechatronics is a matter of integration at three organizational levels where the most substantial needs are found to be at the team-level and the individual level. Furthermore, it is identified that to be able to succeed in mechatronics engineering, managers and engineers must look beyond disciplinary needs. Subsequently, both teamwork and competence management become key issues for management of mechatronics engineering. Finally, computer-supported and model-based development of mechatronics show great potential for successful integration of engineering disciplines, even though such technological aids are still rather immature and need further research and development. A tentative analysis model of organizational integration for mechatronics engineering is also presented and discussed in this thesis.

Based on the presented findings, it is concluded that companies incorporating electronics and software in their mechanical products must effectively manage software and electronics development of these embedded systems. Despite the focus on cross-functional integration in engineering companies, this thesis shows examples of inadequate integration of software and electronics engineering with mechanical integration in organisations dominated by the latter.

Future research studies are needed to investigate the relation between factors influencing the need for organizational integration and potential integration mechanisms. To further understand mechatronics engineering it is important to look deeper into research issues such as changed conditions for the engineering profession implied by multidisciplinary settings, social systems supporting integration of disciplines, changed work conditions due to implementation of technological aids for model-based system development, relationship between product and organizational complexity, organizational designs supporting integration of engineering disciplines, and cross-disciplinary training of highly specialized engineers.

Keywords

Mechatronics engineering, product development, multidisciplinary teamwork, organizational integration, cooperation

Language

English
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List of appended papers

Paper A

Niklas collected all empirical material himself and performed the analysis, with Annika Zika-Viktorsson as an advisor. Niklas performed the realisation of the paper with Annika, Margareta Norell, and Martin Törngren as advisors.

Paper B
Törngren, M., Adamsson, N., Johannessen, P., 2004, "Lessons Learned from Model Based Development of a Distributed Embedded Automotive Control System"; 04AE-59 SAE World Congress 2004, Detroit, USA

The paper was written in co-operation between all three authors and with equal contribution by each author.

Paper C

Niklas collected all empirical material and performed the analysis with Annika as an advisor. The paper was written in co-operation between both authors, with Niklas as the main contributor.

Other publications authored or co-authored


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1 Introduction

This chapter gives the reader an introduction to the industrial change of replacing pure mechanical systems and electrical systems with more synergistic mechatronic systems. Complexity aspects of mechatronics engineering are presented next. The following sections introduce current research and present the purpose of this thesis.

1.1 From mechanics to mechatronics

Companies that traditionally have been developing mainly mechanical products are more and more adding and integrating electronics and software systems into their products, thereby creating mechatronic systems. One industry for which this is highly relevant is the automobile industry (Barron and Powers 1996) as the relative value of electronics in an automotive steadily increases, but many other industries (e.g. robotics and medical equipment) are also influenced.

About 80-90% of new functions in an automobile are electronics based (Steiner and Schmidt 2001; Leen and Heffernan 2002) and it is expected that a third of the total cost for a car will be carried by electronics in 2009 (George and Wang 2002). A retrospective look upon the development of electronics in an automobile is shown in Figure 1. Technologies such as mechanics, electronics, and software are however more and more integrated in order to realize new functions not seen before and for more efficient use of resources, in other terms – mechatronic systems are deployed.

With mechatronic systems new opportunities for innovative technical solutions arise. For example, Electronic Stability Control (ESC) is a mechatronic system designed to electronically detect and assist the driver in critical driving situations. It relies on information from several sensors (e.g. wheel speed, steering wheel, yaw rate) and utilizes actuators (e.g. engine, drive train, brakes), computer networks, and electrical control units distributed on different technical sub-systems and technologies. The system compares a driver’s intended course with the vehicle’s actual movement. When instability is detected, ESC may automatically apply brakes to individual wheels and can also reduce engine torque to help keep the driver on track.
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The technical synergy of a mechatronic system creates critical dependencies between involved engineering disciplines. These dependencies are demonstrated in many ways, mechanical properties may for example be strongly linked to the control system characteristics that in turn are strongly linked to software properties and vice versa. The development of subsystems and technologies may in turn be distributed on a number of organizational departments. As a result, organizational dependencies become critical to manage and co-operation between engineers, representing different technical disciplines and functions, becomes an increasingly important factor to consider for organizations involved in development of mechatronic systems.

1.2 Complexity aspects of mechatronics engineering

Eppinger and Salminen (2001) point out three dimensions of product development complexity: the product dimension, the organizational dimension, and the process dimension. These dimensions may indeed be applicable when describing the complexity of mechatronics engineering. A mechatronical *product* is a very complex technical system with several components, technologies, and functions all interrelated and interdependent. The product development *organization* is also a highly complex system, as several teams and participants experience important interrelations with respect to information sharing about the technical system and about the work carried out. For mechatronics the tasks and assignments must be well executed with the right timing and without excluding any engineering disciplines; these activities are components of a full development *process*. Decisions in one of the three dimensions are rapidly reflected in the other two, and according to Eppinger and Salminen (2001) it is expected that industrial firms in which the interaction patterns across these three dimensions are well aligned would outperform firms for which the patterns are not aligned.
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1.2.1 A diversity of engineers and technologies

Mechatronics engineering concerns the creation of new synergistic products or services that may not be realized solely by one engineering discipline. These engineers have to successfully communicate and coordinate their work in order to create a mechatronic system. Due to traditions and organizational design, they may not be used to work with each other as close as they need to when developing mechatronics.

Different disciplines are joined together in a mechatronic system and their knowledge, dexterities, attitudes, and communication abilities are the foundations for a successful and synergistic design. Different engineering disciplines look differently upon technology (Buur 1990; Bradley 1997). The mechanical engineer primarily deals with matters in three-dimensional space; the electronics specialist becomes involved in topics such as signal processing and communications; and the software engineer mainly deals with logic and algorithms (Figure 2).

1.2.2 Organizational complexity

Development of mechatronic systems requires extensive coordination and integration of knowledge from several engineering disciplines (Bradley 1997; Schoner 2004). Mechatronics engineering traditionally applies a subsystem-based approach. A subsystem-based approach is a product development strategy by which integrated systems are built from technology homogenous subsystems (mechanics, electronics, control, and software). Once the interfaces have been properly defined, development activities are carried out with a pure disciplinary approach. Such an approach does not explicitly push technology development as a result of its closer integration with other technology (Wikander, Törngren and Hanson 2001).

In turn, different engineering specialists are usually geographically distributed and belong to disciplinary departments. One problem for involved co-workers lies in setting a mutual goal as functional goals may be in conflict with system-level goals. The process of goal-setting may also be impeded by the use of discipline-specific language.
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(Adler, Black and Loveland 2003) and a weak team identity as a consequence of fragmented communication (Armstrong and Cole 2002).

It has been proposed (Bradley 1997) that a successful mechatronics design setting is largely dependent on; efficient communication, and collaboration as well as integration of involved disciplines. Mechatronics is dependent on integration on several organizational levels, i.e. project, team, and individual. It is however concluded by Tomkinson and Horne (1995) that the core of integration activities in mechatronics engineering takes part on a team-level and not primarily on an organizational macro-level. Without successful collaboration between engineers, the value of synergy may be less than expected, as mechatronics design is dependent on substantial input from all disciplines.

1.3 Current research

In the traditional manufacturing industry engineering management research has primarily addressed cross-functional integration of the functions marketing, R&D, and manufacturing. There has not been an extensive research emphasis on integration of engineering disciplines within an R&D organization. However, similar problems (e.g. the lack of a common language, the lack of a mutual understanding, different cultures) related to cross-functional integration have been observed in mechatronics settings (Adamsson 2004).

Previous product development research has mainly been referred to Integrated Product Development, New Product Development, Simultaneous Engineering, or Concurrent Engineering (see e.g. Andreasen and Hein 1987; Clark and Fujimoto 1991; Norell 1992; Griffin and Hauser 1996; Ulrich and Eppinger 2004). Such research concerns product development processes, design procedures, design methods, support for cross-functional integration, and front-loaded work. To master cross-functional interdependencies the use of integration mechanisms has been widely discussed and researched (see e.g. Griffin and Hauser 1996; Song, Neeley and Zhao 1996; Browning 1998; Nihtilä 1999; Kahn 2001).

People working within an R&D organization have in most literature been seen upon as a homogenous group of people and referred to as engineers or designers. Interfaces on the organizational macro-level (i.e. between marketing, R&D, and manufacturing) is not the solely most important interface to manage for many companies today, as the need for integration of technical disciplines increases within the R&D organization.

Research on product development management has either concentrated on physical products or software systems, but not on both (Nambisan and Wilemon 2000; Joglekar and Rosenthal 2003). Software development (SD) and New Product Development (NPD) share several similarities, nevertheless has NPD research and SD research generally focused on different aspects (Nambisan and Wilemon 2000). Software literature emphasizes development methodologies, techniques, and process metrics, while the NPD studies typically focus on organizational factors like teamwork, cross-functional integration, internal/external communication in teams, performance, processes, and project leadership (Figure 3).

Mechatronics is a comparatively new technology and so far most research has been driven by and addressed technical matters such as real-time systems (see e.g. Cooling
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1991; Krishna and Shin 1997; Törngren 1998; Tanenbaum and Steen 2001), dependability (see e.g. Laprie 1992; Leveson 1995; Storey 1996), and Systems Engineering (see e.g. Sage and Lynch 1998; Stevens, Brock, Jackson and Arnold 1998; Loureiro, Leaney and Hodgson 2004). A limited number of research studies cover organizational and managerial aspects of mechatronics engineering. Karlsson and Lovén (2003) only found a very limited number of scientific publications that were relevant to this area.

The predominance of technical research about mechatronics is not enough in order to fully understand mechatronics engineering. Technical research is very important, but from the industrial and the academic viewpoint knowledge about organizational integration of engineering disciplines and management of mechatronics engineering is also needed.

Figure 3 An illustration of the deviation in research focus between New Product Development and Software Development (from Nambisan and Wilemon 2000).

1.4 Scope of research

The scope of this research includes development work carried out in both industrial and academic settings with the specific goal of developing mechatronic products.

In this thesis, mechatronics engineering refers to the activities of developing and designing synergistic and integrated mechatronic systems. Mechatronics engineering refer both to the process of developing the products and to the process of developing the technology. The rationale may differ between the processes, but they are both included in the scope of this research.

An operational focus on mechatronics engineering delimits the scope of this thesis as the research has focused on operative work carried out by design engineers.

The present thesis is delimited to include only the R&D organization and the functions within this unit. These functions include disciplinary and/or multidisciplinary workgroups.
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1.5 Purpose

The overall purpose of this research has been to investigate mechatronics engineering in order to understand and explain how co-operation, integration, and knowledge sharing can be supported. This research has been realized by empirical studies in mechatronic development settings in engineering companies, but also by taking part in industrial and academic research projects that develop and study computer-aided mechatronics engineering.

Another purpose was to develop and discuss an analysis model that can be used when analysing integration of engineering disciplines in a mechatronic development setting. The analysis model should provide necessary input to industries involved in mechatronics engineering but also to future academic research studies.

1.6 Definition of central expressions

A number of multi-faceted terms are used in this thesis. The most important and central are presented in this section together with an explanation how to interpret these in the remains of this thesis.

Complex products

Products distinguished by a great number of elements, great number of interactions and interfaces, and/or a high level of heterogeneity.

Cross-functional integration

Interaction and collaboration activities that involve two or more organizational functions.

Discipline

A specific area of knowledge related to an engineering profession, i.e. mechanical engineering or electrical engineering.

Engineering

The work done by, or the profession of, an engineer.

Function\(^1\)

1) What an element of a product or human actively or passively does in order to contribute to a certain purpose. 2) A defined entity of an organization that carry out work with a specific purpose.

Heterogeneity

The quality of being diverse and not comparable in kind.

Integration

Interaction and collaboration that involve two or more parts, which enables them to work more effectively together.

Interface

The way that two subjects or events affect each other.

Mechatronics

\(^1\)Readers should note that function is presented with a two-folded explanation. It is necessary as the work refers both to technical functions and to organizational functions. Subsequent texts will clearly show which explanation that is referred to.
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The synergistic integration of mechanical engineering with electronics and intelligent computer control in the designed manufacturing of industrial products and processes.

**Mechatronics engineering**
Activities carried out by multiple engineering disciplines with the purpose to develop and design synergistic and integrated mechatronic systems.

**Multidisciplinary integration**
Interaction and collaboration activities that involve two or more disciplines.

**Sub-system**
A subset of a system.

**Synergy**
Something additional produced by a combination of two or more entities (organization, human, technical components).

**System**
A defined group of parts that work together as a whole for a particular reason.
2 Theoretical framework

Mechatronics engineering as a research topic has no unique theoretical residence. Mechatronics as a specific discipline has its roots in several engineering disciplines which are indeed more mature and well explored. The theoretical framework for the present thesis is therefore rather divergent in its scope as theories from different research areas needs to be combined.

In order to explain mechatronics as an engineering discipline, the basics of mechatronics are first presented. Organizational and working aspects are then presented with the purpose to put mechatronics in a product development perspective. Research addressing cross-functional integration of marketing, R&D, and manufacturing is also presented, as a similar problem scope was identified and discussed in chapter 1.

2.1 Mechatronics

Mechatronics is considered as an individual technical discipline by many researchers (Grimheden 2002), but in order to treat mechatronics as one engineering discipline the aspects that differentiate mechatronics from other disciplines must be well articulated (Auslander 1996). One recurring facet is synergistic and it is established that from a technical viewpoint mechatronics is a synergistic composition of mechanical, electrical, and software product characteristics.

One definition of mechatronics which may be seen as a milestone is presented in the first refereed mechatronics journal, IEEE/ASME Transactions on Mechatronics: "The synergistic integration of mechanical engineering with electronics and intelligent computer control in the designed manufacturing of industrial products and processes." (Harashima, Tomizuka and Fukuda 1996)

Mechatronics is, however, more than just a combination of different technologies (Dinsdale 1988; Buur 1990), and some researchers consider mechatronics as "a fundamental way of looking upon things" (Millbank 1993). Buur (1990) lists five features that may be achieved from a mechatronical product concept; new technical functions, extension of the range of parameters used for machine control, increased flexibility, compensation of weaknesses of mechanical designs or in mechanical structure design, reduced size and manufacturing costs due to physical integration. Three main requirements for mechatronics engineering proposed by Shakeri (1998) are
to view the system as a whole, to work across the disciplines, and to understand the user/problem domain.

The level of abstraction is also highly different between the technical domains. Mechanical engineering deals with more physical properties of the design whereas software engineering concerns more abstract properties. Bradley (1997) illustrates this relation by putting electronics between the two (see Figure 4). Comparing mechatronics engineering with pure mechanics development, Shakeri (1998) concludes that modelling of logical behaviour is important and production may be simpler, but version handling may be harder to deal with for mechatronics. Shakeri also compares mechatronics with pure software/electronics and states that mechanical parts, control principles and motion are of utmost importance for mechatronics.

2.2 Organizing for mechatronics engineering

Development of complex systems raises great challenges for a product development project. Great efforts on planning and coordination are demanded on the project-level, and both goal and time-focus have to be kept. Established project management tools and techniques may be important for efficient administration and coordination of mechatronics engineering. But, the extensive requirements on cooperation and integration of project members not only calls for rigorous planning, also functional communication channels are needed and learning has to be supported (see e.g. Packendorff 1995; Söderlund 2000; Zika-Viktorsson 2002).

Mechatronics engineering is multidisciplinary, which in turn implies that one particular engineering discipline should not be predominant in the design process (Shakeri 1998). Buur (1990) stresses that mechatronics engineering is characterized rather by a generalist approach than a specialist approach. A generalist approach or a system thinking approach allows a designer to weigh and evaluate the alternatives between solutions presented from the mechanical, electrical, software, or control engineering arenas (Tomkinson and Horne 1995).

2.2.1 Complexity

Westling (2002) proposes five challenges that he sees as extraordinary for complex product development: system-expert bottleneck problems, technical problems, interface problems, coordination problems, and boundary problems. Many parts, both
technical and organizational, are involved in the development of complex products. Organizational complexity is a common consequence of product complexity. However, the impact on the need of organizational integration by product complexity is not well researched and has therefore been seen as insignificant (Gomes, de Weerd-Nederhof, Pearson and Cunha 2003). Although some authors have highlighted this aspect and its relationship to integration (see e.g. Weerd-Nederhof 1998; Kamoche and Cunha 2000), it is still rather unexplored.

Product complexity is discussed by many researchers (see e.g. Flood and Carson 1988; Eppinger and Salminen 2001; Larses and Chen 2003), and common metrics of complexity are the number of elements, number of interactions and interfaces, and level of heterogeneity. As stated, a mechatronic system usually shows a high level of complexity.

The decomposition of a complex system can easily turn into a main challenge. Gulati and Eppinger (1996) point out that decisions regarding the technical system architecture are tightly coupled to the organizational structure and thereby also to the interplay and coordination that takes place between organizational entities in a distributed team environment. For example, if well-defined technical interfaces are described and well-managed, less emphasis on co-location of teams is needed.

2.2.2 Systems engineering

The primary focus of Systems Engineering is to manage the boundaries of a system and the interplay between different sets of subsystems. Systems Engineering (SE) is “the profession associated with the engineering of systems of all types and with consideration given to all of the relevant issues that affect the resulting product or service, or process.” and “systems integration as process integration, knowledge integration, and enterprise integration is very needed.” (Sage and Lynch 1998).

Topics stressed in SE-literature are system requirements, system design, configuration, architectures, system validation and verification, information modelling, and technical system integration activities (see e.g. Sage and Lynch 1998; Stevens et al. 1998; Bahill and Dean 1999; Palmer 1999; Loureiro et al. 2004). Management and team aspects are also discussed in literature (Browning 1998; Browning 1999; Shenhar 1999) and are necessary complements to the body of knowledge that refers to technical system aspects.

2.2.3 Team-work in mechatronics engineering

The traditional subsystem-based approach of mechatronics engineering implies that once the interfaces have been properly defined, disciplinary development activities are carried out relatively separate from each other (Wikander et al. 2001). However, information is constantly exchanged within a project between project members and effective communication is vital to any project (Thamain and Wilemon 1987). In the case of mechatronics engineering the subsystem-based approach usually lead to a distributed team environment, as engineers working with different subsystems are located at an apparent physical distance from each other.

Being a member of a distributed team may imply complicated work conditions. Besides complicated communication patterns, distributed teams may have problems to form
and maintain a strong team identity. The phenomena of exclusion in a distributed team environment is referred to as *out of sight – out of mind* (Mortensen and Hinds 2002), which may cause severe incongruity in a team. In addition, Armstrong and Cole (2002) state that influence of macro-organizational conflicts, traditions, and attitudes may constrain the process of mutual problem-solving in distributed teams.

### 2.2.4 Computer-supported modelling and simulation in mechatronics engineering

Computer-support in product development has to various extents been used in engineering companies for 10-20 years. The main focus has been domain- and discipline-specific modelling and simulation of product characteristics. These tools are usually referred to as Computer Aided X (CAX), where X may stand for Design (CAD), Software Engineering (CASE), or Control Engineering (CACE). According to Shakeri (1998) models for mechatronics engineering should be used to reduce complexity of the work, for improvement of communication ability, to test for correctness, and for trying out designs before executing or realizing them. As the mechatronics discipline has emerged, the trend has turned towards multi-disciplinary modelling and simulation supported by computer-tools.

Recent approaches for mechatronics engineering generally include modelling and simulation as fundamental aspects of the design activities (see e.g. Yan and Sharpe 1994; Butts 1996; Schulz, Rozenbilt, Mrva and Buchenrieder 1998; Craig 1999; Schiele and Durach 2002; Kockerling and Gausemeier 2003). Each approach usually builds upon existing modelling languages originating from individual disciplines. But there are also general approaches not coupled to a specific discipline (see e.g. SysML 2004). Nossal and Lang (2002) propose that model-based system development is one approach to handle complexity, and that it represents an attempt to reduce the distance between engineering disciplines. They conclude that product developers need to gather information about the systems they are working with and gain confidence through modelling and simulation before actually building a system.

Research about management of mechatronic product data involves mainly two areas. Firstly, Product Data Management (PDM) that originates from mechanical engineering and enables consistent archiving of product data, such as structures and digital files (Hallin 2004). Secondly, Software Configuration Management that originates from software development and ease variant and configuration management of software systems. Similarities in scope and usability between these two areas have been noticed (Crnkovic, Asklund and Persson Dahlqvist 2003). But it has also been found that there is no specific tool environment designed for data management of mechatronic systems (Crnkovic et al. 2003), thus separating engineering disciplines in their virtual workspace.

One complication for development of mechatronics is the variety of modelling languages and tools (El-khoury, Chen and Törngren 2003). These languages and tools are not always inherently compatible with each other. Backlund (2000) showed that in order to avoid extensive tailoring work, model integration must be dealt with in early phases of the development process. Most of the tools and languages are developed for specific domains and there is a risk that the organizations get caught in one tool environment, due to the high costs involved in both procuring and adapting new tools.
2.2.5 Competence for mechatronics engineering

As earlier stated, it is proposed that mechatronics engineering has to be treated with a
generalist approach (Buur 1990). Therefore, the importance of competence related to
“the whole picture” is consequently stressed. Given the wide selection of design
alternatives, an engineer involved in mechatronics engineering needs to possess
necessary skills to weigh design alternatives and decide upon which options that are
most suitable for the particular product (Tomkinson and Horne 1995).

Individual competence takes many expressions, and as both Ellström (1997) and
Hoffman (1999) point out that there are many definitions of competence. Hoffman
means that competence has been defined from a number of reference points, e.g. have
psychologists, management researchers, and politicians been using competence with a
number of different purposes. Ellström (1997) refers to a potential capacity when
discussing occupational competence. A capacity that is defined in terms of perceptual
skills, cognitive factors, affective factors, personality traits, and social skills.

In addition to technology-specific skills (e.g. mechanical, software, or electrical
engineering skills), an engineer involved in mechatronics engineering also needs
technology-independent skills. These skills are according to Tomkinson and Horne
(1995) primarily related to system design, decision-making, and teamwork.

A comprehensive mental model of a system is not directly a result of a systematic
approach in collecting system requirements and is not mainly influenced by the formal
description of the system (Hoberg 1998). It is rather a question of forming a mental
model out of strategies, intentions, and a comprehensive view (Hoberg 1998). But the
system level knowledge should not be predominant, as the concept of mechatronics
relies on functional expertise from various disciplines.

Working with development of complex systems, such as mechatronics engineering,
have two main workforce implications. The co-worker specifically has to be aware of
the set of member groups to which the co-worker belongs to and how the system of
groups is interrelated (Adler et al. 2003). The pattern of activities that a co-worker
engages in is according to Adler et al. (2003) the result of that co-worker’s perception
of the underlying relationships among various members of the systems to which he or
she belongs to.

The question of social and interpersonal skills is emphasized with increased levels of
interpersonal interaction (Stevens and Campion 1994), which is highly relevant for
mechatronics engineering (Bradley 1997). It has also been postulated that team-based
work requires each employee to be capable of interacting in a positive and effective
manner (Seers 1989). Zika-Viktorsson and Ritzén (2004) suggest that components of
co-operational project competence include the ability to manage control, support an
open climate, manage negotiations and conflicts, and to act with self-confidence.

2.3 Cross-functional integration

One critical question raised both by Song et al. (1998) and by Gomes et al. (2003) is
whether cross-functional integration always is relevant. To be able to fully utilize the
concept of cross-functional integration, a function-specific and stage-specific strategy
is necessary (Song et al. 1998).
THEORETICAL FRAMEWORK

One negative effect from integrating different functions and disciplines is that the costs may outweigh the benefits. A recurring conclusion is that all organizations do not experience the same need to integrate organizational functions due to specific needs (Gupta, Raj and Wilemon 1986; Griffin and Hauser 1996; Song et al. 1996; Gomes et al. 2003). If not cautious, extensive work on achieving integration may lead to personnel lose their functional skills over time and may lose the focus on their functional goals (Griffin and Hauser 1996). Blind promotion of the involvement of all areas could in some cases be counterproductive and it is critical to identify patterns and levels that result in effective integration.

2.3.1 Barriers and means for cross-functional integration

A number of different barriers to cross-functional integration of marketing, R&D, and manufacturing have been widely discussed in previous research. Hovmark, Nordqvist, Beskow, Zika-Viktorsson and Enerström (1997) divide these barriers into individual barriers, structural barriers, and underlying barriers. Furthermore, Beskow (2000) showed that most apparent barriers were concentrated to social factors, but that collaboration-improving activities were concentrated to physical settings and technological support.

Five barriers synthesized from previous research (Griffin and Hauser 1996; Calantone, Droge and Vickery 2002) will be discussed in the following sections: physical separation of disciplinary expertise, diverged cultural thought worlds, knowledge diversity, language, and organizational diversity.

With each discussed barrier, identified means to overcome the barrier are presented and discussed. These barriers are, however, not present in all organizations and not in all situations. The situational contexts differ, and consequently these barriers should be seen as variables as they may change over time in an organization.

Physical separation of disciplinary expertise

One barrier frequently discussed is physical separation of expertise. Complicated communication patterns and distancing are two possible effects of such separation. Naturally, one frequent solution is to co-locate different persons during time periods. Bringing different departments and disciplines together to the same physical setting may influence integration both positively and negatively. As expected, co-location increases the frequency of interactions. This can be done in several ways, for example by organizing the physical space, job rotation, and visitations (Calantone et al. 2002).

Most authors see co-location of personnel as very positive for integration (Song et al. 1996; Shaw and Shaw 1998), at least in the critical phases of the development cycle. It is important to build trusting relationships, thus reducing conflicts. According to Lenders and Wierenga (2002) co-location is the most effective way of achieving integration, and the most effective mechanism is housing marketing and R&D together concurrently with using an influential cross-functional phase review.

The fact that two functions communicate frequently does not guarantee that they will exchange useful information. Some research shows that the frequency of functional interaction itself does not bear a significant relationship to project outcome (Olsson and Sörensen 2001). Kahn and McDonough (1997) put forward the limited number of empirical studies that have examined the relation between co-location and
performance. However, the limited number of studies shows a positive relation (Kahn and McDonough 1997).

**Diverged cultural thought worlds**

Both Griffin and Hauser (1996) and Calantone et al. (2002) state that diverged cultural thought worlds are one significant barrier to successful integration. Sicotte et al. (2000) follow this reasoning, and say that integration may be hampered due to the existence of diverged cultural thought worlds. Physical barriers and thus isolation solidifies separated thought-worlds and heightens perceptions of personality differences (Griffin and Hauser 1996). Co-workers’ views may be restricted when they are brought together in collaborative settings with different occupational cultures (Huthwaite 1994). Different educational background creates another possible conflict as the differences may result in differing thought views (Prasad 1999).

Calantone et al. (2002) propose solutions to the negative effects of diverged cultural thought worlds in terms of organization of the physical space, job rotation, and informal get-togethers.

**Knowledge diversity**

The difference in training and education has been shown to be one of the most significant factors behind conflicts between engineers and marketers. One important advantage of training is that the new knowledge can help people to avoid differences in their goal setting during projects (Shaw and Shaw 1998). Involvement from project team-members in goal-clarification has been postulated to be one main contributing factor to enhancement of project performance (Ancona and Caldwell 1992).

In order to share domain-specific knowledge, training of engineers in marketing has showed a positive influence on the relationship between marketers and engineers. However, careful management is needed to prevent new skills to become a new cause of conflict (Shaw and Shaw 1998).

**Language**

Specialists develop their own language and there is a risk that this jargon impedes cooperation and communication. When people communicate they seek to find a common ground (Clark 1996). The common ground is the foundation for communication and the reference point for interpreting received information. The search for a common ground may be hindered if the thought worlds are different.

Prasad (1999) put forward that when people start to work side by side both cultural barriers and language barriers begin to break down. Adler et al. propose that in order to support the problem-solving process the co-workers need to have an overlap between their primary vocabulary and the vocabulary of the groups linked to their work (Adler et al. 2003).

**Organizational diversity**

It is suggested by Song et al. (1996; 1998) that one of the greatest barriers to integration is the lack of trust or respect. It derives from that different orientations contribute to a lack of communication, different ideologies, language, and goal orientations. Cross-functional integration may create problems as organizations try to bring people together with different characteristics and different expertise in the pursuit of a unified goal. Cross-functional work has several implications for managers
and therefore it is necessary to encourage an open discussion and debate on different viewpoints.

Prasad (1999) states that it is no advantage with multiple formalized processes, with the scope to integrate different functions including concurrent sessions, if a coherent communication pipeline is missing. It may result in that the processes will slow down the collaborative decision-making due to inefficient and time-consuming discussion with no or little coordination of the dissimilar opinions. Song et al. (1996) also state that a lack of formalized communication structures is one significant barrier to cross-functional integration and it requires managers with special training to coordinate such a diverse set of individuals in the complex process of developing a product.

2.4 Concluding remarks

Successful mechatronics engineering demands an organizational setting that supports communication, collaboration, knowledge sharing, and competence integration. Highly specialized engineers must be supported in developing skills in both system design and collaboration, and they have to be provided with sufficient tools that facilitate cross-disciplinary and cross-functional work activities.

Project uncertainties has to be reduced and tasks need to be clarified to achieve success in product development projects. Success is also dependent on the balance between needed and achieved organizational integration. An imbalance between the two has been proposed as a negative influence on the success of a product development project (Griffin and Hauser 1996; Gomes et al. 2003). Too much integration may decrease engineers’ functional skills and focus on functional goals may be lost, but the costs may also outweigh the benefits of such integration actions.

Consequently, it is rather clear why it is important to study and discuss the relation between a specific integration need and between actions that promote integration of organizational functions and/or engineering disciplines in a mechatronics engineering setting.

2.4.1 A map for studying the project-level interfaces of product development

Researchers have addressed, during the last twenty years, how cross-functional integration of marketing, R&D, and manufacturing should be studied and evaluated. Maps for studying the project-level interface of product development have been presented by Gupta, Raj, and Wilemon (1986), by Rueckert and Walker (1987) and by Griffin and Hauser (1996). The map presented by Griffin and Hauser is shown in Figure 5 and describes situational dimensions, structural/process dimensions, and outcome dimensions. Each dimension includes particular factors that are significant for studying cross-functional integration on a project-level.

Situational dimensions

The situational dimensions shown in the map (Figure 5) summarize the integration need given by several influencing factors. The amount of needed integration is dependent on the specific situation. Two main influencing factors proposed by Griffin and Hauser are the project phase and inherent project uncertainty.
Different phases of a project might require more or less integration activities between disciplines and functions. For example, more integration of R&D and manufacturing may be required in late phases of the product development process, whereas more integration of marketing and R&D may be required in early phases. High project uncertainties may lead to a greater need of integration of involved disciplines. Incorporating new technology and features not used before increase the technological uncertainty. Projects delivering only incremental changes of a mature product may experience a lesser need of integration of disciplines or functions as they only use product and process technologies known to the project.

Figure 5 The map for studying the project-level interface of cross-functional integration of marketing, R&D, and manufacturing (Griffin and Hauser 1996).

Structural/process dimensions
There are a number of investigated actions to achieve integration, so-called integration mechanisms. These actions have previously been organized in terms of Structural dimensions and Process dimensions (Ruekert and Walker 1987; Griffin and Hauser 1996). Griffin and Hauser discuss six general approaches to integration in their map (Figure 5).

Re-location of functional units mainly refers to the physical workspace. Personnel movement is one technique to improve information flows across functional borders as persons moving to another function bring with them contextual information that is important to understand why decisions are made. The informal social system may play an important role but without the right rewarding system groups can satisfy internal customers and thereby jeopardize the companies’ strategic goals. Organizational structure refers to the formal structure of the organization. Functional organization, project organization, matrix organization, coordination groups, team composition, roles and responsibilities are factors emphasized in research that relates to cross-functional integration. Formal integrative processes refer to formal management processes that specifies what tasks to be performed and in which order and by whom.
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It may include product development models, stage-gate reviews, common work procedures, common guidelines and project management activities.

Outcome dimensions

The success of taken actions is evaluated in the Outcome dimensions where success indicators are introduced and used for evaluation of the results. The result is further assessed by predefined success measures. Success indicators have been widely researched, and Griffin and Hauser (1996) refer to several reviews (Booz, Allen and Hamilton 1968; Cooper 1983; Hauschildt 1991). Success can be made assessable by a combination of measures such as financial measures, customer measures, process measures, firm-level measures, and programme measures (Griffin and Hauser 1996).

2.4.2 Proposed research directions for mechatronics engineering

There is no work similar to the map presented by Griffin and Hauser (1996) that is adjusted to the specific conditions and problems concerning complex product development and mechatronics engineering. Such work would give an excellent opportunity for further understanding of the specific problems related to complex product development and multidisciplinary engineering. It is also likely to believe that both industry and academia would benefit from such work.

Future work of mechatronics engineering research shall further investigate the impact on an integration need given by the product complexity, but also consider how the mixture of highly specialized engineering disciplines effects the integration need. Possibilities with computer-supported mechatronics engineering must also be further investigated as well as the relation to integration of organizational functions and/or engineering disciplines.
3 Research approach

This chapter describes and discusses on methodological aspects of the research presented in this thesis. Means for data collection is reviewed and evaluated with respect to the posed purpose of the research.

3.1 A thesis based on qualitative research

Researchers have long debated the relative value of qualitative and quantitative inquiry (Patton 1990). Qualitative research is suitable when a social context and its processes are in focus for inquiry. This thesis is based upon three empirical qualitative studies which all have had an exploratory and inductive approach. All three studies had a specific focus on social contexts of mechatronics engineering, and they also involved questions about technology, design methods, and organization.

Qualitative methods are to prefer when the aim of the study is to better understand any phenomena about which little is yet known. They can also be used to gain new perspectives on things about which much is already known (Strauss and Corbin 1990). Thus, qualitative methods may be applicable in situations where one needs to identify factors that might later be investigated quantitatively. This thesis is based upon qualitative studies, since management of mechatronics engineering is still rather unexplored and a broad picture has to be achieved. The depth and richness of information collected by qualitative methods derives from rather unstructured research questions where different ideas, concepts, and thoughts are gradually deepened. Throughout the three studies, the understanding of mechatronics engineering and its context has steadily deepened.

The role of the researcher in qualitative research is to act as a human instrument as data is acquired, analysed, and interpreted through the researcher. Throughout the three studies, the researcher acted as the human instrument by conducting interviews and taking part in organizational settings involved in mechatronics engineering. The researcher’s engineering knowledge played an important role in understanding the complexity of mechatronics engineering, and as the research has progressed the researcher’s skills of performing research were gradually enhanced.
RESEARCH APPROACH

3.1.1 Designing the research studies
The three different research studies are summarized in Table 1. It is important to pay attention to a number of aspects when research studies are designed. The focus of inquiry has not been the same for all the studies included in the present thesis. As illustrated further in section 4.4, the three studies are interrelated with respect to the overall purpose of the present research. They do, however, differ in focus of inquiry. Study 1 was designed as a multiple case study focusing on design engineers and computer-supported mechatronics engineering. Study 2 was designed as an interactive study focusing on supporting computer tools in mechatronics engineering, and study 3 was designed as a case study focusing on work settings and processes for mechatronics engineering.

Based on the identified technology change discussed in chapter 1, all three studies were executed in the vehicle industry, and particularly in the automotive industry. All informants were selected on the basis that they played central roles in mechatronic development projects. It was important to acquire a broad and varied description, and therefore different engineering disciplines and organizational roles were represented.

3.1.2 Techniques for data collection
All empirical data were acquired from interviews, observations, or project documentation. As shown in Table 1, both semi-structured and unstructured interviews were conducted (Kvale 1996). Semi-structured interviews were conducted in both study 1 and in study 3. In study 3 it was suitable with explorative and unstructured interviews at the point when empirical data already had been collected through observations and semi-structured interviews. The unstructured interviews were performed to probe into the previously received information and statements from the interviews. The aim was to bring out additional nuances in the collected data.

Observations have been done in two organizational settings. In study 2, the researcher took on an interactive role in the process of developing mechatronic systems. As a result, insight and understanding of critical problems developed from the insiders’ perspective. Furthermore, in study 3 the researcher took on a passive and non-participatory role. The aim was to avoid extensive interference with the work progress but still be close enough to directly communicate with the engineers and to observe the activities in the studied group of engineers.

Complementary to the observations in the second study, final project documentation was used in the analysis.

All interviews in this research have been tape-recorded and transcribed by the researcher himself. During the third study, observations from formal meetings were recorded by using designed data sheets based on the study’s initial and explorative interviews. Data from informal meetings and observations in both study 2 and study 3 were summarized in daily field notes.


**Table 1** A summary of the research studies included in the present thesis.

<table>
<thead>
<tr>
<th>Study</th>
<th>Reported in</th>
<th>Purpose</th>
<th>Design</th>
<th>Means for data collection</th>
<th>Time-period</th>
<th>Informants</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Appended paper A</td>
<td>To explore and describe how computer-based and model-based development affects collaboration within multidisciplinary product development from the perspective of the product developers.</td>
<td>Multiple case-study</td>
<td>21 semi-structured interviews</td>
<td>January 2003 – June 2003</td>
<td>One case (n=3) represented a development project to which the interviewed persons were all committed to the project, either part-time or full-time. The interviewed persons (n=21) represented different engineering disciplines (mechanical, electrical, software, and control engineering) and different hierarchical positions (design engineer, project manager, functional manager).</td>
<td>Automotives, trucks, all-terrain vehicles</td>
</tr>
<tr>
<td>2</td>
<td>Appended paper B</td>
<td>To develop and evaluate a suitable tool-chain environment that supports model-based development of embedded control systems.</td>
<td>Interactive study</td>
<td>Participatory observations, Project documentation, Daily field notes</td>
<td>November 2002 – May 2003</td>
<td>4th year engineering students (n=10) which represented three disciplines: Mechanical, Industrial, and Vehicle Engineering. Three supervisors which represented KTH Machine Design and Volvo Cars Corporation.</td>
<td>Automotives</td>
</tr>
<tr>
<td>3</td>
<td>Appended paper C</td>
<td>To understand and explain how team structures influence integration, to investigate competence requirements for mechatronics development as well as managerial implications on multidisciplinary cooperation.</td>
<td>Case study</td>
<td>Non-participant observations, 31 records of formal meetings, Daily field notes, 5 semi-structured interviews, 3 unstructured interviews</td>
<td>February 2004 – May 2004</td>
<td>Main informants (n=3) held central roles in mechatronical development projects and worked mainly with electronics and software. Secondary informants (n~50) were assigned to different roles (system engineer, design engineer, project manager, team leader) and possessed technology-specific competence such as mechanical engineering, control systems, and software architecting.</td>
<td>Automotives</td>
</tr>
</tbody>
</table>
3.1.3 Analysis of data

All data processing has been data-driven and the empirical data has been analysed in an iterative process of reading, quantification, categorization and interpretation (Kvale 1996). Classification patterns and themes slowly evolved while working, organizing, and breaking down the empirical data to manageable units. Transcripts of conducted interviews were analysed with influences from so-called open coding (Strauss and Corbin 1990), which means that the researcher begins with identification of themes emerging from the raw data. These categories were then compared in order to form a comprehensive picture, and later translated into initial research reports.

These initial reports were rich and tightly woven descriptions of the research findings. The translation into a presentable form played a great role in the analysis process. Subsequently, scientific papers were written, each presenting a more narrow scope of the findings.

3.2 Method discussion

In order to evaluate research it is important to distinguish whether a systematic approach and a critical attitude and arguments towards conclusions are present or not (Allwood and Erikson 1999). All studies were accomplished with a systematic approach in terms of planning, designing, and execution. Nevertheless, it is always possible to find weaknesses, and the present research is no exception.

The selection of informants has naturally influenced the presented findings. The somewhat restricted population entails some considerable limitations. All informants have been chosen in discussion with representatives from the participating companies. Two aspects of special interest are noticeable. Firstly, in study 1 the company representatives in one case left out software engineers when planning the study. However, to include multiple engineering disciplines in the already limited case study the researcher successfully addressed this issue. Secondly, it is important to remember that informants in a research study take part on a voluntary basis. All informants had the option to not participate. Only one person in the entire research project, in study 3, rejected to take part as an interviewee.

Furthermore, study 3 mainly reports the perspective of electrical and software engineers who all played similar roles within the organization. However, it is important to report a many-sided view of the findings, as mechatronics itself is a multidimensional discipline. Without a comprehensive selection of engineering disciplines taking part in research studies, it would always be possible to question mechatronic research findings.

The results in study 1 would have been of higher validity with a bigger population in each case and with a broader set of data. In study 3, the results would have been more valid and of a broader representation if more engineering perspectives, such as

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perspectives of mechanical engineers, control engineers, and/or architectural engineers had been included. Even so, the findings presented in the present thesis contribute to the understanding of complexity and co-operational aspects of mechatronics engineering.

Acting as a human instrument of research, the researcher unconsciously adds subjective values into the research process. To strengthen the results and increase the inter-subjectivity, it would have been favourable if the data collection were conducted in co-operation with another researcher. To restrain the negative influence of the subjective values, the intention during the whole research process was to treat findings in a neutral and non-judgemental way.

A neutral position between the research group and the companies should also be aimed for. The research group therefore instigated each research study. The aim was to avoid a disadvantageous relation to the participating companies.

The results of qualitative studies, just like in the present research, are almost impossible to generalize in a broader sense. It is, however, possible to transfer some tentative conclusions to similar situations to contribute to the explanation of phenomena of similar kind. Generally, it is however not achievable to state the actual transferability, only to provide sufficient information that makes it possible for the reader to judge whether the findings are applicable to new contexts (Lincoln and Guba 1985). It is believed that the research process and the findings presented in this thesis and its related publications are informative enough for a reader to judge the transferability.
4 Summary of appended papers

4.1 Paper A: Model-based development of mechatronic systems – Reducing the gaps between competencies?


Research group: Niklas collected all empirical material himself and performed the analysis, with Annika Zika-Viktorsson as an advisor. Niklas performed the realisation of the paper with Annika, Margareta Norell, and Martin Törngren as advisors. All except one of the researchers are engineers. The one exception is Annika, who is a social scientist.

The purpose with the study was to explore and describe how computer-supported and model-based development affects collaboration within multidisciplinary product development from the perspective of the product developers. In this paper it is presented and discussed how model-based development affect collaboration and integration when developing mechatronics.

Empirical base: Three large companies in the Swedish vehicle industry were involved in this multiple case study. Altogether 21 semi-structured interviews were carried out during the first half of 2003. In the Automotive company 11 interviews took place, in the Truck company 6 interviews, and in the All-Terrain Vehicle (ATV) company 5 interviews.

Main findings: The results of the study showed gaps between the different disciplines that work together in developing mechatronics. There were several obstacles present in all three cases that hindered the organizations’ efforts to reduce the gaps between disciplines. The obstacles that were found are divided into four different categories, and are summarized in Table 2. This study shows that the potential of model-based development as an integration mechanism is great but is dependent on certain enablers.
Table 2 Obstacles for integration of different technical disciplines that was found and discussed in Paper A.

<table>
<thead>
<tr>
<th>Obstacle</th>
<th>Case ATV</th>
<th>Case Truck</th>
<th>Case Automotive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-based development</td>
<td>Local strategies, Interfaces inconsistent</td>
<td>Local strategies, Interfaces inconsistent</td>
<td>Lack of guidelines, Two points of reference, Interfaces inconsistent</td>
</tr>
<tr>
<td>Different disciplines – different outlooks</td>
<td>Lack of awareness of other departments’ work</td>
<td>Conceptual confusion with regard to nomenclature</td>
<td>Misunderstanding of terminology</td>
</tr>
<tr>
<td>Organizational support</td>
<td>The product development process was not anchored within the whole organization</td>
<td>The product development process did not fully include system integration</td>
<td>The product development process was not mature enough for interdisciplinary work</td>
</tr>
<tr>
<td>Location</td>
<td>Disciplines geographically dislocated from each other</td>
<td>Disciplines geographically dislocated from each other</td>
<td>Disciplines geographically dislocated from each other</td>
</tr>
</tbody>
</table>

Main conclusions: One main conclusion is that the modelling approach should be aligned within the organization in order to support integration. Currently, within organizations, modelling is done on separate “islands” with no or little exchange of information between them. When there is a certain level of product complexity, such modelling may provide essential support for managing the embedded complexity.

It was also concluded that it is important to clarify the meaning of employed concepts. Different engineering disciplines experienced misunderstandings resulting from different perceptions of the concepts. It would improve communication within the organization if clarification could be made.

Over time, development processes should be adjusted to suit the ever-changing needs of the organization. Any one discipline’s development work tends to be performed quite separately from that of other disciplines until late in the process. This leads to a crucial system integration phase, where different competencies must interact without being able to effect major design changes.

Routines making short-term co-location possible would influence collaboration and communication in a positive direction, since increased interaction might increase understanding and problem-solving efficiency.

Contribution to thesis: Showing the complexity of mechatronics engineering, and the importance to emphasize on all dimensions of mechatronics engineering, not only on supporting tools, as there were other suitable integration mechanisms evident in the studied organizations.


4.2 Paper B: Lessons learned from model based development of a distributed embedded automotive control system


Research group: Martin Törngren and Niklas Adamsson from KTH Machine Design and Per Johannessen from Volvo Car Corporation supervised ten 4th-year students during a six months long student project. The project was carried out as a joint engagement between KTH Machine Design and Volvo Car Corporation. The paper was written in co-operation between all three authors and with equal contribution by each author. All researchers are engineers specialized in mechatronics and integrated product development respectively.

The purpose of the project was to develop a suitable tool-chain environment that supports model-based development of embedded control systems, and in particular function and architecture integration. In this paper experiences and lessons learned from the project were presented and discussed, in particular the challenges and opportunities with model-based development of mechatronics.

Empirical base: The empirical base constitutes besides participatory observations, of project documentation, and daily field notes.

Main findings: One result of the project was a demonstrator set which included the computer tool-chain and a model car demonstrator (scale 1:5) with four-wheel steering, individual braking and four-wheel drive.

The project identified and highlighted both advantages and challenges for model-based and computer-supported development. The main advantage of a semi-complete tool-chain was found to be the design automation, whilst one main challenge lies in the procurement and configuration of such a tool-chain. Another challenge lies in providing the design engineers with a technical system-level competence and with comprehensive design methods for system integration.

Main conclusions: The conclusions from this project were that model-based development has great potential but is still rather immature and there are many factors (organizational, processes) that must be considered to achieve a satisfactory technical integration.

Contribution to thesis: Showing both the challenges and benefits of model-based development as an integration mechanism.

4.3 Paper C: Multidisciplinary product development – a case study of mechatronics engineering

Authors: Niklas Adamsson and Annika Zika-Viktorsson. Submitted for journal publication.

Research group: Niklas collected all empirical material and performed the analysis with Annika as an advisor. The paper was written in co-operation between the two authors, with Niklas as the main contributor. Niklas is an engineer and Annika is a social scientist.

The purpose of this study was to explore integration in a mechatronical development setting, and to understand and explain how team structures influence integration. The purpose was also to investigate competence requirements for mechatronics development as well as the managerial implications of multi-discipline cooperation.

Empirical base: The product development setting in focus for this study was one part of a large complex organization that developing and producing premium-brand automobiles. Data was collected by means of observations and interviews during a period of three months. In total eight interviews were performed, and 31 formal meetings and numerous informal meetings were observed during this period.

Main findings: Mechatronics engineering entails team-based system design in which integration and coordination activities take place on several organizational levels. The two most critical aspects of the setting in this study were team management and competence management. Both multi-disciplinary and functional teams are needed, but it is not an easy task to identify the needs of such teams in their context. Mechatronics development puts extraordinary requirements on both co-operative and technical system skills; it is therefore crucial how competence requirements are met.

Main conclusions: Teams in mechatronics development projects need to evaluate whether their purpose is related to disciplinary or multi-disciplinary tasks. Additionally, the strengths, drawbacks, and specific requirements of a functional versus a multi-disciplinary team setting must be rigorously evaluated.

Furthermore, mechatronics development benefits when project members are given support to develop their co-operative skills in addition to their technical system understanding and awareness.

This study also pointed out the importance of an organizational role for managing the coordination and integration of technical subsystems and interfaces. An important topic that requires further investigation is whether a project manager with an administrative focus or a system engineer with a wide-ranging technical focus should take on this role.

Contribution to thesis: Stresses the importance of managing multidisciplinary teams, but also addressing competence management in mechatronics engineering.

4.4 Relation between appended papers

The three papers present the results of studies with different purposes and objectives. Even so, they are all interrelated to each other with respect to the overall purpose of the present thesis.
- Their context is mechatronics engineering.
- They all concurrently consider different aspects of mechatronics engineering.

The papers all contribute to the thesis with specific and individual results. By using the work presented by Nambisan and Wilemon (2000) which identifies the main areas of research for NPD respectively Software Development, the three papers are mapped onto their triad (Figure 6). The papers cover all dimensions of different aspects that Nambisan and Wilemon identified. Technology is discussed in both paper A and paper B, being the main topic of the latter. The results from paper A pointed out the direction for paper C, leading to that paper C focused mainly on People and Processes.

![Figure 6: The appended papers in thesis mapped onto the different dimensions presented by Nambisan and Wilemon (2000).](image_url)
The overall purpose of this research has been to investigate different aspects of mechatronics engineering in order to understand and explain how co-operation, integration, and knowledge sharing can be supported.

Another purpose was to develop and discuss an analysis model that can be used when analysing co-operation and collaboration in a mechatronic engineering setting. The analysis model is presented and discussed in the final section of this chapter.

Findings of the present thesis show that mechatronics engineering requires a wide perspective on cross-functional integration. It is important to understand that one vital aspect is to manage interdisciplinary cooperation and integration, and not only integration between organizational functions that may include disciplinary and/or multidisciplinary workgroups.

Further findings show that mechatronics is a matter of integration at three organizational levels where the most substantial needs are found to be at the team-level and the individual level, and not primarily the project level. Furthermore, it is identified that to be able to succeed in mechatronics engineering, managers and engineers must look beyond disciplinary needs putting the mechatronic system in centre. Subsequently, both teamwork and competence management become key issues for management of mechatronics engineering. Finally, computer-supported and model-based development of mechatronics show great potential for successful integration of engineering disciplines, even though such technological aids are still rather immature and needs further research.

The author’s background in mechanical engineering and specifically integrated product development has naturally influenced the result of the research. Not being specialized in mechatronics has most likely brought forth findings overlooked by researchers specialized in mechatronics. Previous research mostly focused on technical challenges, but the performed research and parts of the presented literature (Tomkinson and Horne 1995; Bradley 1997; Bradley 2000; Karlsson and Lovén 2003) show that mechatronics engineering is more than just a technical challenge, it also implies great organizational challenges.
5.1 Mechatronics engineering is a matter of integration at three organizational levels

Three levels of integration are distinguished as relevant for mechatronics engineering. These levels follow an organizational ladder with the departmental level at the top, followed by the team level and the individual level. The main integrative and synergistic design activities take place on lower hierarchical levels, i.e. team and individual levels. These findings are in line with Tomkinson and Horne (1995), who propose that the core of mechatronics integration takes part on an individual level. They also suggest that higher hierarchical levels (such as departmental and firm-level) should primarily focus on corporate strategies. In paper C integration activities on a departmental level were identified more as administrative project matters, whereas integration both on a team level and an individual level in a mechatronics setting included collaborative design activities.

Mechatronics also requires an extensive amount of coordination activities. The coordination activities have been shown in paper C to include harmonization and organization of the technical interfaces. Recalling the theoretical framework, coordination with respect to technical interfaces is mainly researched within the Systems Engineering area (see e.g. Sage and Lynch 1998; Bahill and Dean 1999; Palmer 1999).

5.2 Looking beyond disciplinary needs

The importance of support from management for successful mechatronics engineering cannot be overlooked. The managerial objective is to set the scene and support synergistic design activities. It is described both in paper A and paper C that since a majority of product development managers have a mechanical engineering background they tend to underestimate the complexity that mechatronics and software engineering give rise to. A product development approach may remain unchanged if managers lack knowledge about implications given by a mechatronic product strategy. It is crucial to change from a traditional disciplinary view to a synergistic and multidisciplinary view as the earned value of mechatronics is related to synergistic technical integration.

It is vital but complicated to be able to look beyond disciplinary needs and work towards an optimised design of a multidisciplinary technical system. For example, it may be strategically right to replace an expensive and precise mechanical system by a synergistic combination of a cheaper but highly advanced control system and a less precise mechanical system to get an increased performance of the system as well as a decreased cost. Such a decision may be hard to accept for mechanical engineers, as they have to give up their power of critical design knowledge.

Identification of the relation between the product architecture and the organizational structure is one activity where involvement of both representatives from management and effected engineering disciplines should be promoted. The traditional organization of a mechanical engineering company may reflect the physical components of the product, i.e. mechanical systems and electrical hardware systems with distinct interfaces. The coordination and integration activities may be more complicated when an organizational structure reflects product architectures that do not take into account...
the different levels of abstraction and technological heterogeneity of mechatronic systems.

The allocation of system requirements to existing subsystems is a critical design activity. The coordination of system requirements and the following component requirements is identified in the empirical studies as one main problem. As Gulati and Eppinger (1996) point out, decisions regarding the technical system architecture are strongly interconnected to organizational decisions. If the product architecture not is carefully managed, the organizational structure may not be optimised for mechatronics engineering and the work may require extensive and time-consuming cross-functional integration activities.

As reported in Adamsson3 (2003), software competence was allocated to the electrical engineering departments in the early stages of implementing a mechatronics design approach. It is a result of the traditionally tight coupling between electronics and software, and it is therefore more natural to cluster a minority of software engineers with the electrical engineers rather than with the mechanical engineers. But as the relative value of software in the product and the number of software engineers increases, one should reassess how the mixture of disciplines should be set to promote efficient teamwork.

5.3 Effective and efficient team-work is a necessity for mechatronics engineering

As mechatronics engineering is multidisciplinary, development activities require collaboration in multidisciplinary teams. Both a physical and a mental distance between involved engineering disciplines have been identified and discussed in paper A and paper C. Development of mechatronics is commonly carried out in a distributed team with specialists placed on an apparent distance from each other. To the engineers in paper C, the main advantage of reducing the perceived distance between disciplines was the possibility of influencing co-workers’ decision-making related to their own work and problem solving.

One main integration challenge lies in the management of both multidisciplinary and disciplinary teams. Teams in mechatronics development projects need to evaluate whether the team’s purpose is related to disciplinary or multidisciplinary tasks. As concluded in paper C, it should be clearly stated what a team setting should contribute to. Different strengths, setbacks, and requirements of a disciplinary respectively a multidisciplinary team setting must be rigorously evaluated.

Members of distributed and multidisciplinary teams are sometimes forced to move a significant distance in order to meet, a distance that might act as a barrier to interact and achieve mutual understanding. Co-location is widely researched in product development research and findings reveal that placing people with a physical proximity in early phases is important for integration (Shaw and Shaw 1998). Mechatronics research shows that early phases are the most critical for a mechatronics design

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(Coelingh 2000) and multidisciplinary mechatronics team would therefore benefit from being co-located in early phases in the development process.

It is, however, important not to disregard disciplinary teams. These teams play an important role in keeping the disciplinary expertise up-to-date. Engineers may only find full support in technically complicated matters from colleagues with a similar technical competence.

Dependent on the team setting, it may be necessary to appoint an organizational role complementing the teams. Such a role would relieve the design engineers from the full responsibility of managing the coordination and integration of technical subsystems and complementing interfaces.

### 5.4 Providing an organization with the right competence

*Technical system competence* is of vital importance for mechatronics engineering. As also proposed by Tomkinson and Horne (1995) co-operational competence, team competence, and technical system competence have been identified in this research to be central when involved in mechatronics engineering due to the organizational complexity.

Software engineering was organized as a competence belonging to the electrical engineering departments in two of the three reported cases in paper A and in the case presented in paper C. The division shows a manifestation of a traditional organization of physical subsystems and not disciplinary-spanning mechatronic systems. In these cases the disciplinary skills of the engineers are supported as the disciplinary expertise is commonly organized in functional departments.

The diversity of the involved engineering disciplines must be carefully managed. In order to provide a work setting suitable for mechatronics engineering, unique needs of the disciplines must be identified and met. If managers lack a diversified view upon product development competence, mechanical engineering aspects may be predominant which leads to that the unique needs of the different engineering competencies are not stressed in product development competence.

Some researchers point out a hazard of distinguishing the specific needs too much. Claesson (2004) means that it is granted that differences exist, but that there are also similarities that deserve recognition and full attention. It is not recognised and well understood in general that design theories and methodologies may be applicable to the new area of mechatronics. Extensive focus on differences, he continues, may lead to that previously gained experience and approaches are not fully utilized. As Rauscher and Smith (1995) show, it is important for an organization to utilize the knowledge held by different disciplines and especially integrate software issues in the daily problem-solving.

### 5.5 The potentials of computer-supported mechatronics engineering

In paper A and paper B it is shown that supporting technology such as information technology and computer-aided design have great potential for organizational integration and technical coordination. Currently, there are several research initiatives
of developing information systems (Hallin 2004), new modelling platforms (Loureiro et al. 2004), and tools for analysis (Nossal and Lang 2002).

As concluded in paper B available technology is rather immature for cross-disciplinary use and engineers primarily use supporting technology developed for their discipline-specific needs. The most influential factor for the success of model-based and computer-supported development as an integration mechanism was concluded in paper A to be the existence of a coherent strategy for both implementation and deployment.

In theory, all-encompassing computer-tools would include tools that allow product developers to use and share the same product data, no matter the technical discipline to which the product developer belongs. In addition, changes in product design, and the implications of these, would be reflected in another product developer’s virtual workspace since they refer to the same point of reference. There are several research tracks on data management of mechatronical products, but it is stated that there is no specific system designed for data management of mechatronic systems (Crnkovic et al. 2003).

It is not obvious if the benefits outweigh the costs of procuring and using computer tools to support integration of functions and/or disciplines. Drivers for computer-supported and model-based development of mechatronics engineering are discussed in Larses and Adamsson (2004). From the product perspective, it is proposed that the degree of product complexity, product maturity, and product standardisation should be evaluated in order to decide whether a mechatronics engineering setting benefit from extensive computer-support, or if a more social integration strategy should be promoted.

5.6 An analysis model for organizational integration of mechatronics engineering

Development of complex products (including mechatronics) can be problematic. Product development organizations face challenges in management of multi-disciplinary development teams, a highly complex problem scope, and extensive requirements of coordination and integration.

As discussed in chapter 2.4.1, a map for studying the project-level interfaces of product development was presented in 1996 by Griffin and Hauser (1996). Their map intended to act as a framework for future studies on product development management, and especially cross-functional integration of marketing, R&D, and manufacturing. Based on findings presented in this thesis it is stated that their model needs to be complemented in some aspects to suite mechatronics engineering and integration of disciplines within an R&D organization. Therefore, an analysis model adjusted to integration for mechatronic work setting is proposed and discussed here.

The purpose with the completed model shown in Figure 7 is to provide a framework for future studies and analysis of a mechatronics engineering setting addressing the relation between needed integration and deployed integration mechanisms. If there is an extensive focus on integration one downside may be that the engineers’ functional skills will decrease by time and that they might lose focus on their functional goals. Another possible setback from integrating different disciplines is that the costs may outweigh the benefits of such actions. It is therefore important that the model provides necessary input to industries involved in mechatronics engineering but also to future academic research studies.
The model shown in Figure 7 is, in comparison to the original work, extended in both the **Situational dimension** and the **Integration dimensions**. Furthermore, neither influencing factors nor integration approaches proposed in the original work by Griffin and Hauser are disregarded in the analysis model (Figure 7). Although, in contrast to the original work that is rather detailed in its description, the modified model is more general in its description. Only the different dimensions are illustrated in the modified model and no specific influencing factors or specific approaches for cross-functional or cross-disciplinary integration are detailed. More research is needed before such details can be distinguished in the modified model. It is however possible at this point to conceptually discuss these details without drawing any general conclusions.

![Figure 7 Analysis model for studying organizational integration at the project-level of mechatronics engineering.](image)

### 5.6.1 Situational dimension

In comparison to the original research map (Griffin and Hauser 1996) that included **inherent project uncertainty** and **project phase** in the situational dimension, two supplementary influence factors are discussed in the analysis model presented in Figure 7. Further supplementary factors may of course not be disregarded. Therefore, it would be beneficial if further research could converge the set of influencing factor in order to build a better understanding of the situational need of organizational integration for mechatronics engineering.

Based on the results in this thesis it is clear that **product complexity** should be proposed as one main influencing factor to the integration need. It is clear that different aspects (for example the number of elements, number of interactions and interfaces, and level of heterogeneity) of product complexity influence the integration need.

Another influencing factor proposed based on findings presented in this thesis is the **competence profile** of the product development and management personnel. Technical system competence and co-operational competence have been identified as critical for mechatronics engineering. If project members are experienced in mechatronics engineering there might be less need of integration as their experience will be very valuable. The demands on competence are high, and the team members’ knowledge, skills, attitudes, and communication abilities play important roles in achieving an optimised design.
5.6.2 Integration dimensions

Nambisan and Wilemon (2000) used three dimensions (people, process, technology) of product development when comparing New Product Development to Software Development. All three dimensions were described in terms of means to accelerate the product development process. In addition, Eppinger and Salminen (2001) described product development complexity in three similar dimensions (product, process, organization). However, in comparison to Nambisan and Wilemon, Eppinger and Salminen described these dimensions more in terms of dimensions suitable for studying complex product development.

The original map presented by Griffin and Hauser (1996), assorted integration dimensions into structural and process dimensions. By comparing the different suggestions from Eppinger and Salminen (2001), Nambisan and Wilemon (2000), Griffin and Hauser (1996) three dimensions suitable to describe integration mechanisms in mechatronics engineering evolve: process, organization, technology.

The process dimension refers to formal management processes that specifies what tasks to be performed, in which order and by whom. It may include product development models, stage-gate reviews, common guidelines and project management activities that intend to support integration and to reduce the inherent project uncertainty.

Supplementary to the original model (Griffin and Hauser 1996), training is proposed in the analysis model as one possible integration mechanism belonging to the process dimension. Training has been suggested in previous research to be one technique to support integration. The need of training to increase co-operational competence, team competence, and technical system competence is stressed by the complex situation in mechatronics engineering.

The organization dimension refers to actions related to the formal structure of the organization but also to the social system of the organization. It may include such actions as personnel movement, re-location of functional units, and declaration of roles and responsibilities. In comparison to the original work no supplementary changes are proposed in the presented analysis model.

The technology dimension is a supplementary dimension to the original work. It refers both to supporting technology such as information systems and tools for computer-aided engineering, but also to the decomposition of the product as a possible integration mechanism.

Product decomposition is one approach to achieve organizational integration. As already stated, the product complexity influence the integration need. But the decomposition of the technical system into sub-systems may be used as an integration mechanism. Gulati and Eppinger (1996) point out that architectural design dictates the organizational design and determines communication patterns and the feasibility of co-location. In line with findings in the appended papers A and C, they also point out that a well understood interface between architectural chunks minimizes the need for impromptu communication between project teams.

Another approach to achieve organizational integration is to use supporting technology. Information and communications technology (ICT) has been discussed in the theoretical framework of this thesis. For mechatronics, supporting technology also involve multidisciplinary CAE (Computer Aided Engineering) tools. This includes CASE (Computer Aided Software Engineering), CACE (Computer Aided Control
Engineering), and CAD (Computer Aided Design). One significant difference between ICT and such technologies as CASE and CAD is the possibility to perform analysis and synthesis with computer-aided design tools.

5.6.3 Outcome dimension

The success of taken actions can be evaluated in the Outcome dimension (Figure 7). Success indicators have been widely researched and the original work (Griffin and Hauser 1996) refer to several reviews (Booz et al. 1968; Cooper 1983; Hauschildt 1991). In the original work success is based on a balance between needed integration and achieved integration. An imbalance between the two has been proposed as a negative influence on the success of a product development project (Griffin and Hauser 1996; Gomes et al. 2003). Success can be made operational by a combination of measures such as financial measures, customer measures, process measures, firm-level measures, and programme measures (Griffin and Hauser 1996).

This dimension has not been widely discussed in this thesis, partly due to the identified need of explorative research and partly due to the overall purpose of the thesis. Success indicators must be further evaluated and discussed in future research in order to make the presented model more applicable.
Conclusions & Future research

This chapter concludes this thesis by reflecting on the achieved results. Main conclusions of this research project are outlined and presented. Possible directions for future research and implications for industrial practitioners are also presented in this chapter.

6.1 Conclusions

Despite the focus on cross-functional integration in engineering companies, this thesis shows examples of inadequate integration of software and electronics engineering with mechanical engineering in organisations dominated by the latter.

The relationship between an organizational design and product architecture is critical but intricate for mechatronic products. For products that involve technologies with different abstraction levels (for example a mechatronic product), declaring interfaces and assigning responsibilities to organizational functions and role-differentiated engineers is a complicated process. Complex relations and critical dependencies arise on many levels, both in the product and the organisation, as a consequence of the differentiated abstraction levels for components, functions, and sub-systems.

Sufficient technological aids must be provided for multidisciplinary engineering in order to support synthesis, information management, and analysis across disciplinary borders. Such aids are already accessible for disciplinary engineering, but the scope needs to be extended in order to encompass multiple engineering disciplines. Furthermore, it is most important to facilitate system-level design as well as information modelling that include several disciplines.

Cooperation is often complicated for multidisciplinary engineering due to the significant differences in basic terminology and occupational culture of engineering disciplines. Collaborative and communication skills are therefore of specific importance for engineers working in mechatronic development projects.

A two-folded strategy for team management must be kept. It is critical to provide space for both disciplinary and multidisciplinary work activities when product development projects include technologically heterogeneous products.
6.2 Future research

The analysis model presented in chapter 5 will, together with the conclusions presented above, also give input to further research. Future studies need to investigate the relation between the need for organizational integration and potential integration mechanisms in mechatronic settings.

The results from this thesis also give some important input to further studies on multidisciplinary cooperation and knowledge sharing. To further understand mechatronics engineering it is important to look deeper into the following:

- Changes in the engineering profession implicated by multidisciplinary work settings.
- Social systems supporting integration of engineering disciplines.
- Changed work conditions due to the implementation of technological aids for model-based system development.
- Relationship between product and organizational complexity in mechatronics engineering.
- Organizational designs supporting integration of engineering disciplines.
- Cross-disciplinary training of highly specialized engineers.

Future research has to be done with a combination of quantitative studies and more in-depth qualitative studies. In quantitative studies the presented analysis model can be tested. But to gain new perspectives on specific research issues, e.g. changed conditions for the engineering profession, qualitative studies are more suitable for exploration.

6.3 Implications for industry

Some central proposals relevant for management of multidisciplinary product development projects and especially mechatronics engineering, are put forward as concluding remarks. These proposals primarily address practitioners and are not only based on research findings reported in this thesis, as they are also based on personal experiences and reflections from the research process.

- Involve all engineering disciplines early in the product development process in order to take full advantage of knowledge from the different engineering disciplines. Furthermore, it is important to ensure that minorities in the organization are participating and engaged in the daily-decision making.
- Clarify roles and responsibilities to build trustful relations and to support communication. As technologically complicated problems on different abstraction levels are dealt with, mechatronics engineering requires a solid system understanding and comprehensive declaration of responsibilities.
- Clearly assign design teams to disciplinary or multidisciplinary tasks in order to support both system-level design and component-level design. It is important to be aware that both teams have distinct benefits and setbacks for mechatronics engineering.
- It is required that engineers are trained in technologies included in a mechatronic system in order to understand their own role and responsibilities in the complex
work setting. Sharing discipline-specific knowledge and knowing each other’s terminology can support efficient communication and collaboration.

- Evaluate computer-aided design tools with respect to integration of engineering disciplines. When a product reaches a certain level of complexity, all-encompassing computer-tools provide essential support for coping with the increased complexity. Common guidelines should be implemented and interactions between different computer-tools should be aligned in order to share product information between engineering disciplines.


REFERENCES


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